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16. Abstract (Limit: 200 words)

The interaction between microbial heat output (at the expense of the waste being treated) and temperature was identified as the fundamental factor in controlling the composting process. The concept was implemented by means of a temperature feedback control system in conjunction with forced pressure ventilation. Field trials involved raw sewage sludge mixed with woodchips, on a scale of up to 20-ton piles. The new process, which is presently available technology, is called the "Rutgers static pile composting process." Some of its advantages are as follows:

1. A starting moisture content of 75 percent is decreased to 25 percent in 12 days.
2. This tendency to dry represents the decomposition of putrescible (odor-causing) organic matter.
3. No condensate is produced.
4. The need for a curing stage can be assessed in terms of specific, objective criteria.
5. The process is operationally flexible to meet the vagaries of environmental regulation.
6. The drying tendency might be exploited in the preparation of biomass-derived fuel.

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SLUDGE COMPOSTING AND UTILIZATION:
RATIONAL APPROACH TO PROCESS CONTROL

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ABSTRACT

Regulatory pressures, such as the termination of ocean dumping, have stimulated interest in composting as a sewage sludge treatment process. Like other biological waste treatment processes at their inception, composting is presently based on empirical observation. Other processes later evolved toward rational design and control based on fundamental scientific considerations, and composting should be expected to similarly evolve.

Composting exploits the self-heating microbial ecosystem, in which the temperature increases through the accumulation of metabolic waste heat. In this process the relationship between the rate of reaction and temperature differs from that of nonbiological processes. Nonbiologically-mediated chemical reaction rates respond positively to a temperature increase. Biologically-mediated reactions, however, respond positively only up to some limiting value, after which the response is negative. Consequently, the keystone to process control in composting is the interaction between microbial heat output and temperature.

A review of the literature indicates that the thermophilic temperature most supportive of microbial activity in composting (manifested as heat output, dry weight loss, CO_2 production, etc.) is approximately 55°C. The threshold to a significant decrease in activity is approximately 60°C, and a severe decrease is experienced at 70°C. Thus, the composting ecosystem tends to self-limit via excessive heat accumulation leading to inhibitive temperatures. For process control, therefore, the key issue is heat removal in conjunction with the maintenance of biologically optimal temperatures.

To develop such a process control systems, trials were conducted with a mixture of raw sewage sludge and woodchips. Typically, a run was based on three piles, each consisting of 7 wet tons of the mixture. Early runs established that vacuum induced ventilation is not a practicable means of heat removal and temperature control. By the fourth run an effective process control system was developed, based on forced pressure ventilation and temperature feedback. The fifth (and final) run involved one 20 ton pile.

The experimental design for the fourth run provided nominal pile temp-

eratures of 45-60°C, 55-65°C, and 65-72°C. The starting moisture content of 76% was decreased to 22% in 15 days at the lower temperature range, whereas the decrease was to 40% in 18 days at the higher ranges. (Faster drying at lower temperatures is a consequence of the heat output-temperature interaction.) The fifth run was essentially a scale-up at the cooler, more favorable, temperature.

This process control system provides ventilation in response to pile temperature. The following purposes are served: 1) ventilation supplies oxygen, which is required for the aerobic decomposition of the organic matter; 2) ventilation removes excess metabolic waste heat such that microbially favorable temperatures are maintained; 3) ventilation removes substantial amounts of water because the main heat removal mechanism is vaporization (evaporative cooling). With this approach, control is based on the interrelated parameters of heat output, temperature, ventilation, and water removal.

The observations indicated that, fundamentally, there are only two kinds of composting systems, as characterized by the following series of equivalencies.

1) Waste heat retaining ≡ inhibitively high temperatures ≡ self-debilitated microbial ecosystem ≡ slight heat output ≡ slight water removal.

2) Waste heat removing ≡ biologically favorable temperatures ≡ robust microbial ecosystem ≡ substantial heat output ≡ substantial water removal.

The new process, based on the waste heat removing principle, is called the "Rutgers-USEPA-NJDEP-CCMUA static pile composting process". It offers significant advantages with respect to the waste treatment objectives of converting putrescible organic matter to a stabilized end product, and of drying the material. The process provides a range of management options and is operationally flexible to meet changing requirements.

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LIST OF SYMBOLS

A: Area

C: Specific heat

Cpo: Constant pressure specific heat (Cpo(air) - 0.24 Btu/lb °R

h: Enthalpy, relative heat content (Btu/lb)

k: Thermal conductivity of a material (Btu/hr ft °F)

L: Length

M: Mass

m: Mass flow

Q: Heat flow (Btu/hr)

°R: Degrees rankine (the absolute Fahrenheit scale)

R.H.: Relative humidity

T: Temperature

$\overline{T}$: Average temperature

t: Time

V: Volumetric flow

Greek symbols

ν(nu): Volumetric density (ft^3/lb)

π(pi): Constant = 3.14 (no units)

ρ(Rho): Mass density (lb/ft^3)

σ(sigma): Stephan-Boltzman Constant
(0.1713 x 10^{-8} Btu/hr ft °R

I. INTRODUCTION

A. AN HISTORICAL PERSPECTIVE

Biological waste treatment processes typically are based on empirical observation at the time of their inception, and are subsequently evolved toward rational design and control based on fundamental considerations. Well developed examples are provided by the activated sludge and anaerobic digestion processes. Although the activated sludge wastewater treatment system was first described in 1914 (1), until recently only empirical control parameters were available. In the 1960's a new parameter was devised based on a fundamental attribute of the system (2). This is mean cell (or sludge) residence time, which is a function of the growth rates of the microbes that comprise the activated sludge culture. Similarly, although anaerobic sludge digestion has been practiced since 1891 (3), rational control of the process did not begin to take shape until around 1929 with a report on the interactions among organic acid concentration, pH, and methane formation (4). Derivative research related these findings directly to the methane-forming population (5). It is apparent through these examples that rational control and optimization of biological waste treatment processes is a consequence of an understanding of the underlying microbial ecosystem.

Widespread interest in composting specifically for the purpose of sewage sludge treatment originated, in the mid-1970's, with the development of the "Beltsville-USDA static pile process" (6). This development coincided with the early stages of a broad examination of sludge management practices, provoked by the scheduled termination in 1981 of dumping at sea(7). An important advantage of composting for land-based disposal is that the process residue is generally acceptable aesthetically. Thus, composting has begun to receive serious attention as a sludge treatment process.

In the brief period since its introduction, the Beltsville process has demonstrated the feasibility of composting within the institutional framework of sewage treatment (8). Nonetheless this process is empirical, as an historical perspective would lead us to expect. Like earlier approaches to biological waste treatment, sewage sludge composting will doubtless undergo an evolutionary development based on the microbial ecosystem underlying the process.

B. PROJECT SCOPE

The waste treatment objectives accomplished through composting are: organic matter stabilization, drying, and the destruction of pathogenic organisims. Stabilization and pathogen kill are traditional objectives, whereas drying has only recently emerged as an objective (9, 10).

This report concerns process performance in static pile composting. Performance is judged in the context of the stabilization and drying objectives. Pathogen kill is considered only peripherally, in the Discussion section.

II. FUNDAMENTAL CONSIDERATIONS*

This section of the report is a critical review of the literature on microbial and physical aspects of composting.

A. MICROBIAL SELF-HEATING AS THE BASIS OF COMPOSTING

Although heat is produced by all metabolic activities, it usually dissipates quickly so that no local temperature increase is apparent. An exception is biological self-heating, which refers to the spontaneous temperature increase within freshly assembled masses of organic material. Self-heating occurs if conditions of nutrition, moisture, and oxygen are supportive of aerobic respiration, and if the mass provides sufficient insulation to retain part of the metabolic heat output. Generally the heat is microbial in origin, except that metabolically active plant and animal tissue, if present, may make a contribution early in the temperature ascent. Any non-microbial contribution dwindles, however, because the enzymes are inactivated by unfavorable temperatures and by microbial attack. Thus with rare naturally occurring exceptions, or where microbes are deliberately excluded, biological self-heating is a microbial phenomenon. Composting exploits biological self-heating for the purpose of solid waste management.

At the highest temperatures attainable through bacterial action self-heating can pass, under restrictive conditions, from a biological to a non-biological causation (11, 12). Unlike its robust biological counterpart, chemical self-heating is initially delicate because the rate of heat output is low until temperatures well above the biological range are reached. Nevertheless, under favorable conditions chemical self-heating can become vigorous, even to the point of leading to spontaneous ignition. In its present form, however, composting is based strictly on self-heating brought about by microbes.

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*P. F. Strom and D. J. Suler contributed to this section.

B. INTERACTION BETWEEN BIOLOGICAL ACTIVITY (E.G. HEAT OUTPUT) AND TEMPERATURE

The self-heating microbial ecosystem is first established when fresh organic material is assembled. It then quickly enters into a period of dynamic and intense change. This soon gives way to a condition resembling steady state, followed by decline and senescence. The system thus behaves in a teleonomic, or goal directed, manner (13). Process control in composting, as in other biological waste treatment processes, consists of speeding the system toward its goal.

The course of development in composting is readily described in terms of temperature. Yet, while this is a critically important parameter, it is really just the most conspicuous manifestation of underlying events. To examine these events in the absence of unnecessary complication we consider, at this stage of the analysis, only research in which biological activity was not restricted by lack of nutrients, moisture, or oxygen. By maintaining these factors within biologically favorable ranges they are minimized as variables. This permits an undistracted search for cause and effect relationships between biological activity and temperature.

We first consider experiments in which the interplay between heat output and temperature was given free rein in the adiabatic apparatus (IIB1). Secondly, we consider experiments designed so that temperature was fixed. This was to examine the effect of temperature on decomposition efficiency (IIB2a) and community structure (IIB2b).

1. Heat Output - Temperature Interaction

A unique feature of self-heating, and the keystone of process control in composting, is the interaction between biological heat output and the temperature of the mass. Heat output is a manifestation of microbial growth and metabolism at the expense of organic matter, whereas the temperature is a complex function of the specific heat of the material and heat gains and losses through various mechanisms. The interaction became resolvable with the pioneering development of the adiabatic apparatus by A. G. Norman and his associate (14). In this device heat losses from the experimental chamber, charged with self-heating material, are made up from an external source so as to stimulate a condition of perfect insulation and heat retention.

Oxygenation is with air preheated to match the experimental temperature. Also, the air is prehumidified to prevent the loss of heat and moisture through evaporative cooling. This type of experiment is terminated before nutrients are seriously depleted.

A variety of materials prone to self-heat have been examined with the adiabatic apparatus, including straw (14) several kinds of hay (12, 15), and wool (16, 17) and a mixture of municipal refuse and sewage sludge (15). There is little doubt that the information from this line of research, and related bacteriological studies, pertains to biological self-heating regardless of the nature of the material. Similarly, such information pertains to processes based on self-heating, regardless of the economic motivation. The following summary outline relies in part on a previous review of the literature on composting (18).

Self-heating is initiated by mesophilic microorganisms and is carried forward by thermophiles. Mesophiles may be defined as organisms "...with mid-range temperature optima, and thermophiles with high temperature optima" (19). The mid-range is given as 13°C - 45°C, and the high range as 42-69°C. Mesophiles and thermophiles capable of bringing about self-heating are dependably present in organic materials. Although "extreme thermophiles" grow at higher temperatures in aquatic systems (20), their involvement in the self-heating of organic masses is problematic. Rather, self-heating appears to be the domain of mesophiles and "moderate" thermophiles.

Soon after the organic material is assembled the proliferation of mesophiles and the accompanying heat output elevates the temperature (Fig. 1). For a while the increasing temperature is favorable, causing an acceleration in growth, heat output, and the temperature increase. Later, a tendency toward self-limitation is expressed as the temperature becomes unfavorably high, suppressing growth and its manifestations. Finally, as the mesophilic temperature tolerance limit is exceeded, this population collapses, heat output declines sharply, and the temperature ascent pauses.

Because the temperature is now suitable for thermophiles these events are repeated in a second, high temperature, stage (Fig. 1). As before, a period of autocatalytic behavior leads to self-limitation. Consequently, the temperature stabilizes at a peak value sustainable by a relatively low density of active thermophilic cells and their accompanying low rate of heat output.

In summary, self-heating can be described succinctly in the language of systems dynamics. Starting at mesophilic temperatures a feedback loop involving heat output and temperature is established. The feedback is positive until approximately 38°C is reached, whereupon it switches to negative. The self-heating then passes to a thermophilic stage and the pattern is repeated. In this stage the feedback switches from positive to negative at approximately 55°C.

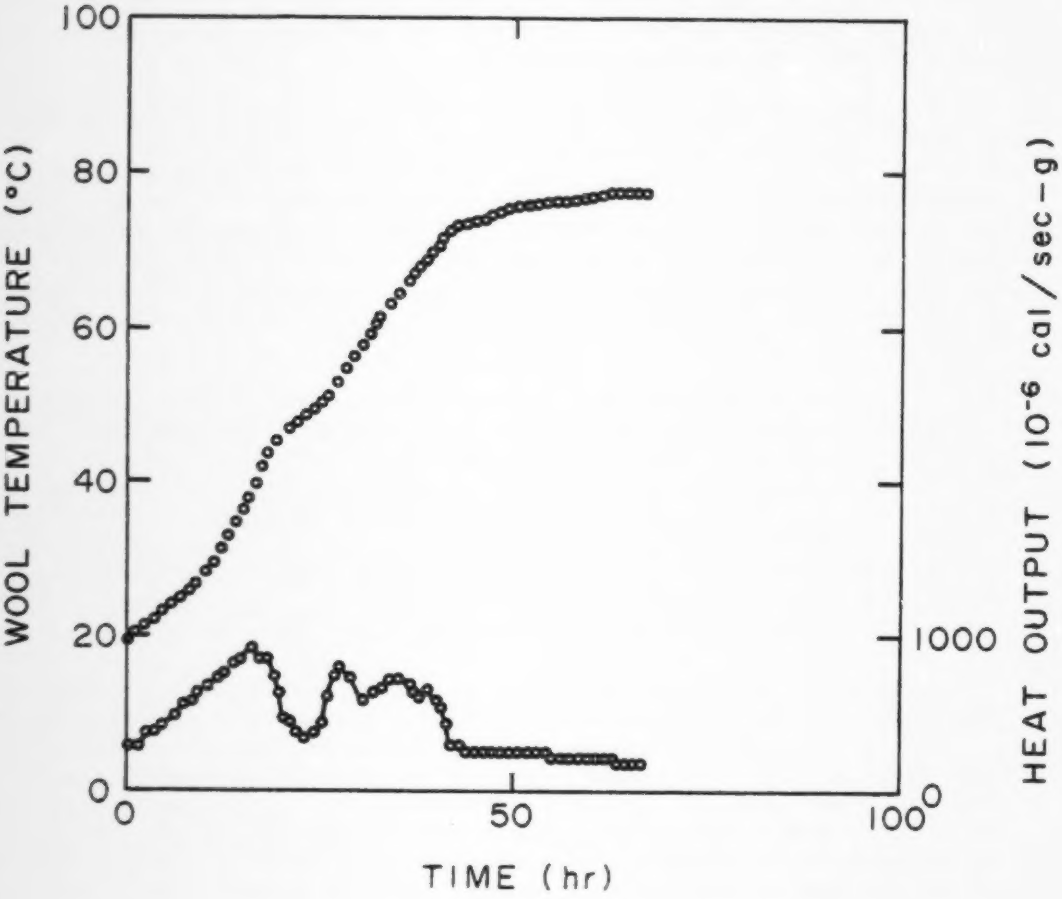

FIG. 1. WET WOOL SELF-HEATING IN THE ADIABATIC APPARATUS
FROM: WALKER, I.K. AND W. J. HARRISON, NEW ZEALAND J. AGRIC. RES. 3:361, 1960. (REF. & NOTES, 16.)

(REPRODUCED BY PERMISSION.)

2. Fixed Temperature Experiments

With respect to solid waste treatment, the temperature ascent is but the precursor to the high temperature stage in which, presumably, the process objectives are accomplished. This section of our analysis is based on experiments specifically designed to test the effect of temperature on decomposition, and on community structure.

Such an experiment is designed as follows: 1) Physical and chemical factors are maintained as constant as possible at nonbiologically limiting levels throughout the experimental period. This refers to substrate, moisture content, oxygen content, pH, etc. 2) A constant, mimimum temperature is established by design, and the elevation above this value as the result of self-heating is minimized. 3) Time is provided for the microbial community to equilibrate to the test conditions, including the temperature. 4) Ecosystem activity at the different temperatures is measured by specific objective criteria. In summary, the experiment must be designed so as to isolate and measure effects caused solely by temperature. Certain reports that do not meet these conditions are nevertheless usefully examined (21).

We know of five studies that conform to the above outline (22-28; see Table 1). One of these involved wool (24) and the others real or simulated municipal refuse. In all of the studies the effect of temperature was measured in terms of chemical and/or physical responses (II B 2a), although Strom's research (27) mainly concerned the effect of temperature on population structure (II B 2b).

a. Decomposition efficiency

Two experimental approaches were taken to provide a fixed temperature, or at least an acceptably narrow test range. The first approach (22, 23) relied upon self-heating in insulated chambers to reach the design temperatures. Some of the chambers had water-jacketed inner walls through which cooling water could be circulated. This was to remove heat and arrest the temperature ascent a some design level. Depending on the criterion used, decomposition was fastest at from 52°C to 60°C, whereas 48°C, and 69° -73°C gave inferior results (Table 1). The investigator (Wiley) considered volatile solids reduction, CO_2 production, and O_2 utilization to be the most reliable criteria. Using these as the criteria he concluded that "decomposition efficiency" was best at 56°C.

The second approach, to establish a minimum temperature, was to immerse the experimental chamber in a temperature-controlled waterbath (24, 26), or to house the chamber in an air incubator (27), or to supply heat with an electrical heating element mounted inside the experimental chamber

Table 1. The optimum thermophilic temperature for decomposition efficiency *

	Wiley (1956 and 1957)						Rothbaum (1961)		Jeris and Regan † (1973)	Suler and Finstein (1977) -				Strom (1978)
										CO_2 prod		Dry wt loss		
Temp deg C	Dry wt loss	Vol. Solids loss	H_2O prod	CO_2 prod	O_2 util	Decomp effic **	CO_2 prod	Heat output	O_2 util	10% O_2	18% O_2	10% O_2	18% O_2	Dry wt loss
48	0.52	0.56	0.64	0.64	0.63	0.65			0.83	0.71	0.85	0.60	0.56	
50							0.84	0.70						
52									0.93	0.73	0.85	1.00	0.68	
50-57														1.00
56	0.88	0.95	0.66	1.00	0.84	1.00			0.99	0.97	1.00	0.80	0.84	
55-61														0.71
60	1.00	1.00	1.00	0.87	0.82	0.97	1.00	1.00	1.00	0.92	0.96	0.84	0.60	
60-65														0.67
62	0.69	0.72		0.79	0.92	0.86								
64	0.81	0.79		0.88	1.00	0.95			0.96	0.67	0.72	0.48	0.56	
65-69														0.14
68									0.87	0.63	0.39	0.32	0.12	
70							0.94	0.57						
69-73	0.61	0.65	0.73	0.76	0.76	0.77								
72									0.74	0.04	0.05	0.16	0.00	
74							0.53	0.28						
78							0.05	0.00						

* Relative number based on a maximum value of 1.00 for each parameter noted in each report, (see Ref. & Notes 22-28).

† Based on the theoretical parobolic curve in the original report.

- Percent O_2 refers to the residual in the exhaust gas.

** this is based on Wiley's suggestion (see text).

(25). Using this approach there is some increase above the established temperature, at biologically favorable temperatures, caused by self-heating (24, 27).

These results also show that decomposition was suppressed at temperature approaching the upper end of the range encountered in composting (Table 1). Decomposition efficiency, measured at CO_2 production, heat output, O_2 uptake, and weight loss, was maximal at 52°C to 60°C.

b. Community Structure

The studies summarized above were of the "black box" type in that the ecosystem's response to temperature was measured in terms of overall activity (e.g. heat output, CO_2 production). In our laboratory we have, in addition, taken the approach of determining the effect of temperature on community structure (27, 29). Representative pure culture collections were obtained by plating compost samples onto trypticase soy agar incubated at the minimum compost production temperature. The isolates were characterized and identified using accepted procedures (e.g. 30). By design the investigation emphasized the genus Bacillus, as thermophilic members of this group are frequently reported to be the dominant cultivable bacteria in self-heating materials (18).

Composts produced at 50°C to 57°C and 55°C to 61°C yielded similar species diversity index values (Table 2). When production was at 60°C to 65°C the index was markedly lower, and at 65°C to 69°C it was zero. A species diversity index of zero means that only one type of organism is observed, which, in this study, was B. stearothermophilus.

While there is no known relationship between decomposition efficiency and community diversity, this attribute is nonetheless of practical significance. The correlation between diversity and ecosystem stability is a widely recognized ecological principle (31). Its pertinence to process stability in the context of waste treatment needs no special demonstration. Similarly, with respect to microbes, community diversity implies also metabolic diversity --i.e., the capacity to attack a wide range of organic substrates. This is especially desirable in view of the presence of industrial organic compounds in wastes.

3. The Temperature Optimum

Adiabatic and fixed-temperature experimentation thus indicate that the highest temperatures attainable through biological self-heating are inimical to organic matter decomposition, as measured by several objective criteria. Based on these data, the best estimate is that the optimum thermophilic composting temperature for organic matter decomposition is 52-

60°C. Furthermore, the data indicate that considerably higher temperatures, such as are commonly encountered in field practice, exact a severe operational penalty.

This conclusion, with respect to measurements of both ecosystem activity and community structure, is consistent with the well established effects of temperature on individual microbial species. The rate of metabolic activity (e.g., measured as growth) of a given microbe is directly related to temperature up to some optimal level, but above that level the relationship is inverse. As the temperature tolerance limit is approached activity declines precipitously. Likewise, the number of species able to grow at thermophilic temperatures is inversely related to temperature. Of the perhaps 50,000 total fungal species, for example, only about 65 are able to grow at 50°C, only 20 at 55°C and none have been found which can grow at temperatures above 62°C (19). Similarly, among the 22 "major" species of the bacterial genus Bacillus described in Bergey's Manual (32), at least 16 are capable of growth at 45°C, 9 at 50°C, 5 at 55°C, 3 at 60°C, and only 1 at 65°C or above.

C. VENTILATION

Gas exchange, or ventilation, is necessary in composting, hence the need for porosity. Ventilation results from nondeliberate and deliberate causes. In the nondeliberate category are passive diffusion, and convective updraft set in motion by the temperature differential between the composting mass and the ambient air. Deliberate practices to promote ventilation include agitation of the mass, as in mechanically assisted windrow processing, and forcing air through the mass, as in the Beltsville static pile process. Ventilation serves three purposes, as outlined below.

1. Oxygenation

In composting the heat is generated through aerobic respiration (*i.e.*, the microbes utilize O_2 as the terminal electron acceptor). A function of ventilation is to supply O_2 so that it is not a limiting factor (33). Information is needed, therefore, on the relationship between the O_2 content in the interstitial atmosphere and biological activity, particularly as this would elucidate the boundary between a nonlimiting and a limiting condition. Most of the reports of O_2 levels in composting masses lack a suitable experimental framework (34), a problem reminiscent of that already described for temperature.

Table 2. Effect of temperature on microbial community diversity in a mixture of composting table scraps and newspaper (abbreviated from Strom, 1978)

Composting temperature °C*	Random Isolates from composting material			Species diversity index‡
	No. of isolates	No. of genera	No. of species	
50 - 57	57	3	7	0.67
55 - 61	65	2	7	0.66
60 - 65	62	1	3	0.07
65 - 69	46	1-2†	1-2†	0

---

[*] The lower value is the temperature of the incubator housing the composting chamber, and the higher value is the peak temperature reached through self-heating.

[†] Depends on the identity of lost colonies.

[‡] Shannon index $\bar{H} = -\Sigma P_i \log P_i$ = no. of individuals in the i^{th} species as a fraction of the total no. of individuals in the sample (see reference 31). Lost colonies were excluded.

One investigation was designed so that cause and effect were reasonably well isolated from other variables (26). Air was passed through refuse composting in experimental chambers so that the residual O_2 levels in the exhaust streams approximated 18%, 10%, and 2% (v/v). The experimental temperatures were from 48°C to 72°C, at 4°C intervals. In general, CO_2 production associated with a residual of 18% was only slightly greater than with 10%. Production was much less, however, with a residual of 2%. One special test at 56°C employed O_2 enriched air to provide exhaust residuals of 25% and 35%. These resulted in similar quantities of CO_2 as the 18% and 10% residuals.

It is concluded that 18% O_2 in the exhaust stream represented a nonlimiting condition and that 10%, while adequate for processing, was perhaps at the edge of a limiting condition. The 2% residual represented an overt O_2 limitation.

2. Heat Removal

We defer a detailed consideration of heat removal until later sections of this report. Meanwhile, suffice it to say that vaporization (evaporative cooling) and convection are the main heat removal mechanisms. Both are associated with ventilation.

3. Water Removal

The only significant mechanism of water removal is the vaporization associated with ventilation. Through this mechanism the composting mass dries, eventually to the point of suppressing biological activity. We return to this subject later in connection with the experimental observations.

D. WATER

In this section the roles of water in composting are considered.

1. Water as a Coolant

The involvement of water in removing heat through vaporization was already suggested. It is estimated that, under favorable composting conditions, this mechanism accounts for 4/5 of the heat removal (see V).

2. Water Requirement for Biological Activity

Although moisture content is a convenient and useful process control parameter, fundamentally it is a poor means of comparing the water status of dissimilar organic materials in relation to microbial availability (35). Generalizations regarding moisture content as a determinant of biological activity must, therefore, be viewed with caution. In the literature on waste treatment composting, however, water status is reported only as moisture content, and an oft-repeated observation must serve -- that a moisture content of perhaps 50% to 60% seems to support vigorous activity. Lower values are inhibitive because life depends on water. Higher values may interfere with oxygenation by restricting gas exchange.

3. Metabolic Production of Water

Water is an end product of aerobic metabolism. Wiley (23) estimated that in the composting of refuse 0.11 to 0.31 gm water was produced per gm of volatile solids in the initial charge. Thus, metabolic activity results in both water removal (through evaporative cooling) and the production of "new" water.

4. Moisture Content as a Measure of Product Quality

Great economic benefit is realized through water removal. A dry product is desirable for numerous reasons, such as to decrease weight, metabolic activity, and the tendency of the material to cake. Furthermore, a dry residue can be burned more easily for energy generation, should this prove feasible. In general, dryness facilitates resource recovery and ultimate disposal, and moisture content is therefore an important measure of product quality.

III. MATERIALS AND METHODS

A. SITE

The Rutgers University, Cook College, Department of Environmental Science, pilot scale composting research facility was located at the Camden County Municipal Utilities Authority (CCMUA) sewage treatment plant at Second Avenue and Jackson Street, Camden, N. J. At this location the CCMUA has a composting facility of the Beltsville-USDA static pile type, where the sludge from their Jackson Street and Baldwin Run treatment plants is routinely processed (total, 20-25 dry tons/day). Although sludge and woodchips, and supportive services, were provided through the routine operation, the investigation reported herein was independently designed and executed.

On the experimental site (Fig. 2) a shed housed the instrumentation and control systems. The shed was heated and ventilated to prevent temperature extremes.

B. EXPERIMENTAL MATERIAL

1. Sludge

Approximately 90% of the sludge, on a dry weight basis, came from the Jackson Street plant, where sewage treatment consists of primary settling. The remainder came from Baldwin Run, where partial digestion is accomplished in an Imhoff tank. Thus, the experimental material was essentially raw fresh sludge.

The Jackson Street plant serves a mixed residential-industrial area, with the Campbell Soup Company as the largest industrial contributor. The sludge is preconditioned with the addition of about 2 pounds of polymer (Allied Colloid Percal 728, a chloride based cationic polyelectrolyte) per ton dry solids, followed by dewatering through a belt filter press. This yielded a cake of approximately 25% solids (oven dry weight expressed on a wet basis). Analyses of the sludge are available (36).

2. Woodchips

Virgin woodchips from hard and soft woods (nominal dimensions, 1" x 1" x 1/4") were obtained from Chipar, inc., New Egypt, N. J. The woodchips were used to form a base for the composting pile, as the bulking agent for mixing with the sludge, and to form a cover over the composting pile.

C. MIXING

For runs 1 and 2 the sludge and chips were mixed in a revolving batt, four cubic yard capacity, Artsway Silamix Wagon. For runs 3, 4, and 5, a system was available in which sludge (by weight) and wood chips (by volume) were combined in a preset ratio, mixed in a continuous pug mill, and discharged to a dump truck.

D. MECHANICAL VENTILATION

Four inch diameter corrugated flexhose (Agway Inc., Englishtown, N.J.) was used for the ventilation ductwork. This was nonperforated, or perforated, as required (Figs. 2, 3). A squirrel cage blower (Dayton, Inc., Chicago, 2C820) with a 1/3 h.p. motor (Dayton #5K586a) provided either vacuum induced or forced pressure ventilation, depending on whether the flexhose was coupled to the inlet or outlet side of the blower. In the vacuum induced mode a condensate trap (Fig. 4) protected the blower.

E. ASSEMBLING THE PILE

In preparation for pile construction woodchips were spread to form a base. For runs 1, 2, and 3, the base was 8 to 10 inches thick, and the flexhose was placed on the surface of the base. For runs 4 and 5 the base was 12 to 14 inches thick, and the flexhose was buried within the base. Using a frontend loader (3.5 yd.^{3} bucket) the sludge-woodchip mixture was placed on top of the base. Material was sequentially apportioned to each pile a bucket load at a time to insure uniformity among piles. The pile was then covered with woodchips to a thickness of 6 to 10 inches. Finally, the control and monitoring devices were inserted.

F. BLOWER CONTROL

For runs 1 and 2 the piles were ventilated by one of the following means: passive only (no mechanical assist); blower controlled by a timer with 30 min cycle (Dayton 2E130); blower continuously on.

For runs 3, 4, and 5, a temperature actuated blower control system was used (Fig. 5). A temperature controller (Fenwal Inc., Ashland MA., Series 551), with an adjustable temperature set point, continuously received and interpreted a signal from a thermistor (Fenwal, 28-232806-304) in the pile. When the signal indicated a temperature less than the set point, the controller actuated the blower through the timer. When the temperature was above the set point the controller directly actuated the blower until ventilation decreased the pile temperature (in the vicinity of the thermistor) to less than the set point (Fig. 6).

For run 3 the thermistor was naked. For runs 4 and 5 the thermistor was shielded by threading it into a length of 3/8" iron pipe.

G. MONITORING ARRANGEMENTS - AUTOMATIC

1. Temperature

Except for control purposes, as described above, temperature was determined with thermocouples made of 20 guage copper-constantan wire (Thermoelectric Corp., Saddle Brook, N. J.). For interior-determination the thermocouple was mounted on a wooden dowel. In early runs there was one thermocouple per dowel, housed in an aluminum cap at the end of the dowel (Fig. 7). In later runs additional thermocouples were taped to the dowel at 1 foot intervals. For surface determination the thermocouple was placed on the underside of a flat board (Fig. 8). Thermocouple leads were organized through the use of subjunction boxes at each pile, through a main junction box, and finally they were wired to a recording monitor (Doric Scientific Corp., Cedar Grove, N. J., Digitrend 2000). The monitor was housed in an immobilized van. Thermocouple leads did not exceed 250 feet in length.

2. Carbon Dioxide Determination

a. Sampling

Gas sampling probes (Fig. 9) were inserted into the piles. The gas samples were cleaned before determination by passage through a condensate trap consisting of a vacum flask packed with glass wool. A four-point multiplexing system (Interscan, Inc. Chatsworth, CA) sequentially interrogated three different pneumatic inputs (Figs. 10-13) using a sample pump of nominal 1.0 liter/minute flow, and a 5 liter/minute purge pump. The fourth sample point was used as an ambient purge between samples. Sample cycles were 30 minutes long and were initiated every four hours (Fig. 13).

b. Determination

The gas samples collected by the multiplexing system were passed through an infrared CO_2 analyzer (Beckman, Los Angeles, Model 315). The data were interpreted using calibration curves supplied by Beckman. The instrument was usually calibrated twice a week.

H. MONITORING ARRANGEMENTS - MANUAL

1. Oxygen Analysis

Oxygen was determined with a portable O_2 analyzer (Bacharach Inst. Co., Pittsburgh, PA. Model 524). The gas sampling probes described above were used.

2. Collecting Samples of Composting Material

A clamshell type posthole digger (5 inch diam) was used to obtain samples. The woodchips were removed, and the remaining sample material was sealed in plastic for transport to the laboratory. Determinations were initiated immediately upon receipt in the laboratory, usually within 4 hr of sampling.

3. Laboratory Determination

a. Moisture

Sample material was dried to a constant weight in an oven maintained at 104°C. Moisture content is expressed on a wet weight basis (% moisture = $\frac{\text{wet weight}-\text{dry weight}}{\text{wet weight}} \times 100$), as is the convention in the composting literature.

4. pH

Sample material was wetted with distilled water to make a slurry. The determination was by pH meter.

IV. RESULTS AND TECHNICAL EVALUATION

In this section the data are reported and evaluated in terms of the design of the succeeding runs. A general evaluation is deferred until the Discussion and Final Considerations sections (pages 37-59).

A. FLEXHOSE PLACEMENT

As described in Materials and Methods, the flexhose was placed on top of the woodchip base for runs 1, 2, and 3, and it was buried within the base for runs 4 and 5. Because the composting mass offers more resistance to airflow than the woodchip base, the buried position probably gives superior performance in terms of uniform introduction of air, with better distribution and less short-circuiting. Use of the other position in the earlier runs causes minor akwardness in certain external comparisons, as noted later. Internal comparisons, such as within runs, are not affected.

B. RELATIONSHIP BETWEEN CO_2 AND O_2 - A SPECIAL STUDY

Although this study was part of run 2 we present it at the outset to aid the evaluations.

On day 7 of run 2, gas samples were withdrawn from various locations of piles 2A and 2C (23 samples per pile) for the determination of CO_2 and O_2. This was repeated on day 14 for pile 2C (17 samples). The levels of CO_2 ranged from 0.1% to 6.5% (Fig. 14).

The pairs of values from each sample were summed ($CO_2 + O_2$), and the sums were analyzed statistically (37). The three sets of sums are not significantly different ($p<0.01$). The overall mean of the sums is 20.78 ($\sigma = 1.01$).

Thus, over the range of CO_2 values observed in this study (up to ca. 7%), the level of O_2 can be estimated from CO_2 data through the relationship: % O_2 = 20.78-CO_2. This is convenient as CO_2 was determined by automatic procedures.

C. RUN 1

The purpose of the first run was to assess the utility of vacuum induced ventilation as a means of temperature control. Experimental details are provided in Table 3 and Fig. 15.

1. Results

The temperature profiles reflect the strength of ventilation (Figs. 16 - 23). Piles 1A and 1B, in which mechanical ventilation was intermittent, displayed similar profiles (Figs. 16 - 20). In these piles the temperature peaked from 70°C to 79°C, depending on probe position. This was followed by a series of fluctuations which were more frequent and drastic at the positions closer to the edges. In pile 1C (Figs. 21 - 23), which was continuously ventilated, the temperature peak was from 58°C to 77°C, depending on probe position. The peaks were followed by sharp declines and then, in latter stages of the run, by some recoveries.

Higher intersitial CO_2 contents were associated with the intermittent ventilation (Figs. 24, 25). Based on its relationship to CO_2, the minimum O_2 content was 16.5% (observed in pile 1A at hr 100).

2. Evaluation

In retrospect the ventilation system used in the early runs was suboptimal in that the flexhose was place on top of the woodchip base rather than being buried in the base. Starting with run 4 the flexhose was buried in the base.

Despite this placement of the flexhose, it is presumed that pile 1C (and perhaps 1B) was more strongly ventilated than piles constructed according to the recommendation of the Beltsville group (6). This is based on a comparison of blower size, timer schedule, and pile size. For pile 1C these were: 1/3 hp, 100%, 7 ton; the Beltville recommendations are: 1/3 hp, 20%, 53 tons.

Table 3. Design of Run 1, and weather conditions

Dates: September 1 to 22, 1978

Ambient air temp.: $\bar{T}$ high = 26.7°C
$\bar{T}$ low = 15.6°C
T mean = 21.1°C, range 10.0°C → 31.7°C

Rainfall: 2.86 inches total in 6 occurrences

Sludge/woodchip ratio: 1/1.5

Flexhose placement: on top of woodchip base

Basis of control: timer

Thermistor placement: NA

	Pile		
	1A	1B	1C
Pile wet wt. (lbs. approximate)	14,000	14,000	14,000
Blower direction	vacuum induced	vacuum induced	vacuum induced
Timer schedule			
%	1.7	13.3	100
min/min cycle	0.5/15	2/15	15/15
Temperature set point	NA	NA	NA

NA - Not Applicable

A problem with the comparison is that the recommendation is based on the flexhose buried in the woodchip base, whereas in this run the flexhose was on top of the base. Therefore, the relative values given above exaggerate the strength of ventilation in the experimental piles *vis a vis* the recommendation. Nonetheless, the experimental range is so broad that it doubtless straddles the recommendation.

Thus judging from these results, vacuum induced ventilation is not promising as a means of controlling temperature. Even with continuous ventilation (pile 1C) the temperature at positions 1,2, and 5 peaked at severely inhibitive levels (77°C, 74°C, and 76°C), while at position 3 the peak was inhibitive (6[illegible]°C). This prompted us to consider, for the first time, the relative merits of the two possible directions for ventilation.

D. VACUUM INDUCED VS FORCED PRESSURE - A THEORETICAL EVALUATION

The two possible directions of ventilation are examined in relation to the movement of air, and the potential for causing nuisance odors.

1. Air Movement

It can be argued that forced pressure ventilation is capable of moving more air and heat with a given power expenditure than vacuum induced ventilation. This stems from the following physical relationships. i) It is easier to move air from the flexhose duct into the pile than vice-versa. This is because vacuum may draw material towards the duct possibly clogging the air passageways. ii) In the vacuum mode moisture condenses in the flexhose duct, decreasing the cross-sectional area available to airflow. iii) The temperature differential between the pile and the ambient air establishes a potential for convective updraft through the pile. This potential is exploited through forced pressure ventilation, whereas it is suppressed through vacuum induced ventilation. iv) Pressure gives a more uniform heat distribution because it induces evaporative cooling in the part of the pile that is most highly insulated. Thus heat is carried toward the edges, which tend to be undesirably cool. Vacuum induced ventilation has the opposite effect, drawing heat from the edges and concentrating it in the center. v) Although the alternative modes move essentially equal volumes of air, the mass flow is approximately 15% greater with forced pressure ventilation (38). This is because the blower moves ambient air, which is cool and dense relative to the gas exiting from the pile. Since efficiency for cooling and oxygenation is related to mass, rather than to volume, the pressure mode takes more complete advantage of the installed blower capacity.

2. Nuisance Odors

The purported reason for adopting vacuum induced ventilation, in conjunction with "scrubber piles", was for odor control (6). We question this reasoning as follows: i) Standard operation (6) calls for the blower to be off 4/5 of the time, during which convective updraft vents exhaust without benefit of the scrubber pile. ii) It is probable that the residence time of "a molecule of composting atmosphere" is longer in the pile cover than in the scrubber pile. This is because in the forced pressure mode a diffuse low velocity flow enters the cover, whereas in the vacuum induced mode a confined high velocity flow enters the scrubber pile. This suggests that the cover pile is the more effective odor control device.

Regardless, odor control should not be considered primarily in terms of a "tack on" in the form of a scrubber pile or pile cover. Rather, odors should be prevented as an integral part of the overall approach to process control. This is equivalent to providing favorable conditions of temperature and oxygenation, among other factors, to insure a vigorous attack on the putrescible organic materials.

E. RUN 2

The observations from run 1, and the above theoretical evaluation, are reflected in the design of the second run (Table 4, Figs, 15, 26). The piles were ventilated as follows: no mechanical ventilation (i.e., passive ventilation only); continuous vacuum induced ventilation; continuous forced pressure ventilation.

For this run only the temperature data were plotted by computer, while the CO_2 data were plotted manually as ususal (Figs. 27 - 44). (The "special" CO_2 data presented in Fig. 14 are not included here.) The gaps in the plots represent an accidental shutdown of the automatic data collection system.

1. Results

Near the top of the passively ventilated pile the interior probes (Figs. 27 - 33) recorded prompt temperature ascents peaking at 80°C (2AII) and 79°C (2A2I). Near the center of the pile 72°C was reached (2A4I). Relatively high temperatures persisted in the post-peak period.

The previous experience with continuous vacuum induced ventilation (pile 1C) was essentially repeated in that prompt temperature peaks were recorded (2BII, 75°C, 2B2I, 79°C, 2B4I, 79°C, 2B5I, 78°C). Again, the tem-

Table 4. Design of Run 2, and weather conditions

Dates: October 13 to November 3, 1978

Ambient air temp.: $\bar{T}$ high = 19.1°C
$\bar{T}$ low = 5.6°C
T mean = 12.4°C, range 0°C → 27.2°C

Rainfall: 0.80 inches total in 3 occurrences

Sludge/woodchip ratio: 1/1.3

Flexhose placement: on top of woodchip base

Basis of control: timer

Thermistor placement: NA

	Pile		
	2A	2B	2C
Pile wet wt. (lbs. approximate)	14,000	14,000	14,000
Blower direction	NA	vacuum induced	forced pressure
Timer schedule			
%	0.0	100	100
min/min cycle	0/30	30/30	30/30
Temperature set point	NA	NA	NA

NA - Not Applicable

perature fluctuated widely.

With continuous forced pressure ventilation the highest temperatures recorded were as follows: 2CII, 65°C and 68°C, 2C2I, 50°C; 2C3I, 35°C; 2C4I, 44°C; 2C5I, 28°C. There was a prompt retreat from the peak temperatures.

With respect to surface temperatures (Figs. 34 - 42) the upper area of the pile represented by probe series 1S, 2S, and 3S, is first considered. The highest peak values were on the passively ventilated pile (2A1S, 79°C; 2A2S, 76°C, 2A3S, 72°C). The next highest peak temperatures were associated with continuous forced pressure ventilation (2C1S, 68°C; 2C2S, 65°C; 2C3S, 63°C). Finally, the lowest peak values were with continuous vacuum induced ventilation (2B1S, 60°C; 2B2S, 51°C; 2B3S, 48°C).

The lower area of the pile was represented by probe series 4S, 5S, and 6S. These peak temperatures were similar for all piles (range 60° - 64°C).

The CO_2 content (Figs. 43, 44) in pile 2A was as high as 18% early in the run, and thereafter ranged between 1 to 6%. The range in pile 2B was 0.5 to 6%. Except for two brief periods, in pile 2C the CO_2 content was less than the instrument sensitivity limit.

2. Evaluation

The results from pile 2A indicate that, independent of any mechanical assist, convective updraft is a significant factor in ventilation. Evidence for this comes from the pattern of interior and surface temperatures, in that the higher values were associated with the positions near the top of the pile.

Pile 2B was reminiscent of pile 1C, which was of like design, in that continuous vacuum induced ventilation failed to prevent the initial temperature ascent from reaching inhibitive levels. This emphasized the poor prospect of utilizing vacuum as a means of temperature control.

With continuous forced pressure ventilation excessively high temperatures occurred only at position 2C1I. Indeed, the mesophilic range was not exceeded at 2C3I, 2C4I, and 2C5I. Since heat output is greater at mesophilic temperatures than at thermophilic temperatures (see VB1), it is concluded that forced pressure ventilation is the superior means of removing heat. Only this mode of ventilation was used hereafter.

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* Additional comments in Chapter 6.

F. RUN 3

This was essentially a "shakedown" of the temperature feedback control system described in Materials and Methods. A large amount of ice was unavoidably associated with the woodchips used to cover pile 3C, which added water as it melted.

The timer schedules and temperature control set points are given in Table 5, and the temperature probe locations in Figs. 15, 26. The CO_2 sampling probes were positioned in the core of the piles. The record of blower "on" and "off time (Figs. 45 - 47) provides a visual representation of the roles of the temperature controller, timer, and thermistor (see also Fig. 6).

A power overload shut down the blowers at hr 288, and these were returned to service at hr 328. Meanwhile, the event recorder malfunctioned so that there is no further record of blower "on" and "off" time. For the present purposes, we consider only the results from time zero to hr 288.

1. Performance of the Control System - Mechanical and Electrical

During the first 66 hours the blower for pile 3A (55°C set point) was actuated solely by timer, indicating that the pile temperature in the vicinity of the thermistor was less than 55°C. At hr 66 blower "on" time first exceeded that scheduled by timer, indicating that the controller responded to a thermistor temperature of at least 55°C. At hr 72 a period of continuous blowing started, terminating at hr 114. Thereafter, demand for the blower subsided to the point that it was on approximately 50% of the time.

The blower associated with pile 3B (65°C set point) was on 100% of the time for only a brief period (hr 70 to 72). Thereafter, the blower was on approximately 25% of the time.

The blower for pile 3C (75°C set point) was controlled by timer for the entire period of record. This indicates that temperatures as high as 75°C were not reached at the position of the thermistor.

The blower for pile 3A sometimes alternated between on and off as frequently as every few seconds. This undesirable characteristic is attributed to two factors: 1) the thermistor is highly sensitive to temperature variation; 2) the placement of the flexhose duct on top of the woodchip base was faulty in that it tended to introduce the air as a point source to the area immediately overhead. The thermistor was in this area. The following remedial measures were taken in subsequent runs. First, an iron pipe was used to shield the thermistor from direct contact with the airstream. Second, the flexhose was buried in the woodchip base to introduce the air into the composting mass as a diffuse source.

Table 5. Design of Run 3, and weather conditions

Dates: March 2 to March 22, 1979

Ambient air temp.: $\bar{T}$ high = 13.9°C, $\bar{T}$ low = 1.6°C; T mean 7.8°C, range -6.7°C → 20.6°C

Rainfall: 2.34 inches total in 4 occurrences

Sludge/woodchip ratio: 1/1.3

Flexhose placement: on top of the woodchip base

Basis of control: temperature feedback

Thermistor placement: one foot above flexhose

	Pile		
	3A	3B	3C
Pile wet wt. (lbs.)	13,500	13,500	13,100
Blower direction	forced pressure	forced pressure	forced pressure
Time schedule			
March 2 to 4			
%	3.3	3.3	3.3
min/min cycle	0.5/15	0.5 /15	0.5/15
March 4 to 22			
%	5.0	5.0	5.0
min/min cycle	0.75 /15	0.75/15	0.75/15
Temperature set point	55°C	65°C	75°C

Thus, although certain deficiencies were uncovered, the system proved to be basically sound mechanically and electrically.

2. Performance of the Control System - Pile Temperature

The interior temperatures of pile 3A (Figs. 48 - 50) generally peaked at inhibitive values well above the set point (e.g. 70° at 3AII). The exception was at 3A2I, where the peak was 54°C. At this position, however, the post-peak temperatures were lower than the set point level.

Similarly, in pile 3B (Figs. 51, 52) the temperatures were generally higher or lower than the set point. Position 3B5I was exceptional in that the temperature range of 65° to 70°C was close to the set level. The performance of Pile 3C (Figs. 53 - 55) is essentially irrelevant as it was controlled by timer throughout the period of record.

Peak surface temperatures (Figs. 56 - 64) were generally higher than peak interior temperatures.

Thus, irrespective of the blower shutdown incident, the system did not perform satisfactorily with respect to the control of interior temperatures. Two remedial measures were already noted: shielding the thermistor, and burying the flexhose within the woodchip base. Evaluation of the temperature data indicated a further remedy. This was to "lead the target" by setting the temperature controller at a value lower than the desired pile temperature.

Because of inadequate temperature control the observations on pH, CO_2, and moisture content (Figs. 65 - 68) are of only marginal interest. Furthermore, the problem with ice, noted above, complicates any evaluation of pile 3C performance.

G. RUN 4

The control system modifications noted previously (shielding the thermistor, flexhose placement, "leading" the temperature target) were incorporated into this run (Table 6). The thermocouples were positioned in a grid transect at 1 foot intervals through the pile midsection (Fig. 69). The thermistor and a thermocouple were at position 1, and the CO_2 probe was in this vicinity. Samples for the determination of pH, moisture content, and for the odor test, were taken from approximately between position 6

Table 6. Design of run 4, and weather conditions

Dates: May 10 to May 31, 1979

Ambient air temp.: $\bar{T}$ high = 23.0°C
$\bar{T}$ low = 13.9°C   T mean 18.5°C, range 8.9°C → 30.6°C

Rainfall: 5.09 inches total in 12 occurrences

Sludge/woodchip ratio: 1/1.75

Flexhose placement: buried in base

Basis of control: temperature feedback

Thermistor placement: one foot above base centered over flexhose

	Pile		
	4A	4B	4C
Pile wet wt (lbs)	13,560	13,500	13,530
Blower direction	forced pressure	forced pressure	forced pressure
Timer schedule			
%	6.7	6.7	6.7
min/min cycle	1/15	1/15	1/15
Temperature set point	45°C	55°C	65°C

and 10. Blower duration is given in Figs. 70 - 72, and temperature in Figs. 73 - 92.

1. Results

a. Time zero to hr 500

In pile 4A the temperature feedback control system was actuated at hr 12, and from this point until hr 150 the blower was on 70% to 100% of the time. Subsequently, demand for the blower slackened, terminating at hr 352. Thereafter, the blower came on only as scheduled by timer.

Near the termistor (4A1) precise temperature control was achieved. Between hr 12 and 352 the only significant departure from 45°C is represented by the 53°C value (hr 112), which occurred during a period of 100% blower "on" time. This indicates that the blower capacity was barely sufficient to restrain the temperature ascent.

Control was less precise to the left of the thermistor (positions 4A2, 4A3, 4A4, and 4A5). In this direction, the greatest departure from set point was at the outermost position. As usual, higher temperatures occurred in the uppermost areas of the pile. This relationship is illustrated by comparing the temperatures at positions 4A1, 4A6, and 4A13.

Overall, between hr 12 and 352, the observed temperatures ranged between 25°C (4A3) to 63°C (4A5 and 4A13). Only 1.8% of the values, however, were greater than 60°C. The significance of this temperature boundary is discussed later (V B).

For pile 4B blower demand commenced at hr 26, as marked by a brief period of 73% "on" time. Thereafter the blower was on between 10% and 48% of the time. The last indication of blower demand was at hr 214. Temperature control was precise near the thermistor (position 4B1) during the period of blower demand, and deteriorated to the left of this position and in the upward direction. Overall, between hr 26 and 214, the temperature range was 18°C to 78°C (both extremes were at 4B5). Fifty eight % of the values were greater than 60°C.

For Pile 4C blower demand commenced at hr 28 and terminated at hr 84. Blower "on" time was slight. Temperature control was precise at the thermistor location (4C1) during the period of blower demand, and less precise elsewhere. The temperature range for the hr 28 to hr 84 interval was 64°C to 74°C (various probes).

The CO_2 levels are given in Figs. 93, 94. In pile 4A CO_2 peaked at 14% prior to the commencement of blower demand. This part of the record is missing for Pile 4B. For Pile 4C the peak value was 12%. Thereafter, in all of the piles the level decreased to 5% or less.

The starting pH was 6.3 and this increased at a different rate in each pile, to approximately 8.2 (Fig. 95). A secondary increase in pile 4A started after hr 380.

The starting moisture content (Fig. 96) was 76%. In piles 4B and 4C (55°C and 65°C set points) this decreased to 40% in 18 days. In pile 4A (45°C set point), the moisture content decreased to 22% in 15 days.

b. Hr 500 to hr 1120 (termination)

The run was continued to determine whether the decline in activity, manifested in the temperature decline and the reversion to timer schedule, was caused by substrate or water limitation. The procedure was to rewet the central portion of the pile, where the thermistor and thermcouples were located. The problem of obtaining representative samples was especially severe during this part of the run, and reliable data on moisture content were not obtained. The rewetting procedure, and a summary of the results, are given in Table 7. The observations are presented graphically in Figs. 97-102.

In all of the piles the initial rewet caused a temperature ascent. In piles 4A and 4B, but not in pile 4C, this was sufficient to re-actuate the temperature feedback control system. Each subsequent rewet caused a temperature response.

2. Evaluation

Table 7. Rewetting trials - run 4

Time (hr)	Pile(s)	Rewet method	T^{o} Response			Blower demand		
			4A	4B	4C	4A	4B	4C
500	4A	Pumped injection*	Yes	NA	NA	Yes	NA	NA
635	4B, 4C	Poured on top	NA	Yes	Yes	NA	Yes	No
805	4A, 4B, 4C	Fire hose	Yes	Yes	Yes	Yes	Yes	No
970	4A, 4B, 4C	Fire hose	Yes	Yes	Yes	Yes	Yes	No

*Approximately 120 gallons of water was pumped through a gas sampling probe which was inserted into various parts of the piles.

Four 20 gallon containers filled with water were carried to the top of each pile and emptied.

Each pile was watered at a low rate with a fire hose for approximately 30 min.

**Each pile was watered at a moderate rate with a fire hose for approximately 10 min.

NA = not applicable

a. Time zero to hr 500

The experimental objective was accomplished in that the piles were maintained approximately at the intended temperatures. Run 5 was designed as a scale-up of pile 4A.

b. Hr 500 to hr 1120 (termination)

The discussion of these results is deferred as they have no bearing on run 5.

H. RUN 5

Run 5 was a scale-up, designed to maximize biological activity, from the 7 ton pile 4A to the 20 ton pile 5 (Table 8; Figs. 103, 104). This necessitated the use of four 1/3 hp motors with attached blowers (Fig. 3). Two lengths of flexhose were buried in the woodchip base, and each end was connected to a blower. There were control changes, by intent and by accident, during the run. These are summarized as part of Fig. 105. Additionally, there is a gap in the temperature record (Figs. 106 - 122).

1. Results

We first consider the period from hr 0 to 140, during which the thermistor at position 6 was in service. For the first 50 hrs the precision of temperature control was comparable to pile 4A in that the thermocouple at poisition 6 recorded, essentially, the set point temperature (see Fig. 108, probe 6). Control was less precise in the lateral and vertical directions relative to probe 6. Starting at hr 50 the ventilation system was unable to arrest the temperature ascent even though blower "on" time was 100%. The peak temperature at probe 6 during this period was 65°C. In the lateral direction, closer to both of the twin flexhoses, the peaks were approximately 60°C. As in pile 4A, the higher temperatures occurred in the upper part of pile 5. Starting after hr 110 the temperature started to recede, although the temperature record is incomplete at this point.

Additionally, probes were positioned near the end of the pile (Fig. 103, 104). Peak temperatures of approximately 60°C were recorded at these locations (Figs. 122, 123).

At hr 140 the thermistor at position 6 was disconnected and the therm-

Table 8. Design of Run 5, and weather conditions

Dates: August 2 to August 15, 1979

Ambient air temp.: $\bar{T}$ high = 30.5°C
T mean = 25.3°C, range 13.3°C to 33.9°C
$\bar{T}$ low = 20.0°C

Rainfall: 3.21 inches in 6 occurrences

Sludge/woodchip ratio: 1/2

Flexhose placement: two sections buried in woodchip base

Basis of control: temperature feedback and manual (see text)

Thermistor placement: one foot above base

	Pile 5 (one only)
Pile wet wt. (lb.)	40,000
Blower direction	forced pressure
Timer schedule	
%	13.3
min/min cycle	2/15
Temperature set point	45°C

istor at position 39 (Fig. 124) was put into service. The controller relay malfunctioned, however, as indicated in Fig. 105. At hr 160 the blowers were manually turned on to give 100% "on" time, deliberately bypassing the temperature feedback control system. This resulted in a rapid drop in temperature at all locations.

The starting pH of 5.2 increased to 7.6 by hr 50 (Fig. 125). From this point until hr 120 the pH decreased slightly.

Carbon dioxide was monitored at three locations (Figs. 126, 127). The pattern of CO_2 concentration reflects the extent of blower "on" time.

The starting moisture content of 71% decreased to 44% during the first 120 hr of operation (Fig. 128). Thereafter, moisture content varied little.

2. Evaluation

Although the ratio between blower capacity and pile size was comparable for pile 4A and pile 5, the ambient air was less efficient as a coolant because of seasonal changes. (The mean ambient temperatures were 18.5°C and 25.3°C, respectively.) This may have contributed to the inability to completely arrest the temperature ascent in the vicinity of the thermistor after hr 50.

Otherwise, during the first 120 hrs of operation, the performance of pile 5 was similar to pile 4A. Thus, the scale-up, in general, was successful.

The behavior of the pile after the temperature feedback control system was bypassed is considered in the Discussion (VH).

V. DISCUSSION

A. CONSPICUOUS EXAMPLES OF THE HEAT OUTPUT - TEMPERATURE INTERACTION

The concept of the heat output-temperature interaction was developed on the basis of previous investigations (Sec. II). The experiments reported herein were not designed to further investigate the interaction, but rather the purpose was to employ it in process control. The data are consistent with the concept and occasionally provide clear illustrations of it, as in the following examples:

1. Temperature Non-Controlled Runs

i. Consider pile 2A, for which blower "on" time was zero. Ventilation was therefore by passive means, and it may be presumed that heat loss from the pile was at a low rate. Soon after the pile was formed the temperature increased to inhibitive levels and, with some fluctuations, stabilized at such levels. It appears that at the biologically inhibitive temperatures heat output declined to a low rate approximately matching that of heat loss.

ii. Consider pile 1C, for which blower "on" time was 100% in the vacuum mode. Position 1C1, 1C2, and 1C5 are of greatest interest as these represent the pile interior. Despite the strong ventilation the temperature promptly increased, indicating that microbial heat output initially exceeded heat loss from the pile. After reaching inhibitive levels, however, the temperature declined rapidly. This can only be attributed to a sharply decreased heat output, as the opportunity for heat removal was unchanged. After a lengthy period at lower temperatures there was a second major temperature ascent. It appears that the debilitated microbial community was not made instantly robust by a sudden decrease of temperature from a harsh to a benign level. Rather, a significant time period was necessary for the rehabilitation.

2. Temperature Controlled Runs

Finally, we seek a pair of identical temperature values associated with grossly different circumstances. Consider probe 4A1 at hr 112 and probe 4C1 at hr 122, at which times both were at 53°C. With respect to 4A1, the 53°C value represents a departure from the set point of 45°C during a period of 100% blower "on" time. Evidently heat output was so intense that the blower was barely able to restrain the temperature ascent. In contrast, at 4C1 the 53°C value was a point in a decline from the peak temperature during a period of 8% blower "on" time scheduled by timer. Since a high temperature was not sustainable even though ventilation was slight, heat output must have been slight.

B. THERMISTOR PLACEMENT CONTROLLER SET POINT COMBINATION

1. The Temperature Range

A temperature gradient is established in passively ventilated piles, and the gradient is enhanced by forced pressure ventilation. Underneath the thermistor (between it and the woodchip base) the temperature is less than the controller set point value, whereas above the thermistor (between it and the cover) the temperature is above this value. The problem, therefore, is to select a combination of thermistor placement and controller set point which provides a favorable temperature range. The boundaries of such a range must be considered.

As developed in Section II, a severe operational penalty is exacted at excessively high temperatures. Based on Table 1, as extended in Table 9, there does not seem to be a comparable penalty at the lower temperatures encountered in composting masses. Indeed, under Rothbaum's experimental conditions (24) activity at mesophilic temperatures (26°C and 37°C) was greater than at thermophilic temperatures (50°C and 78°C), and he summarized other evidence for this relationship. This indicates that the need to prevent inhibitively high temperatures has no low temperature corollary.

We suggest that 60°C marks the threshold to significant operational

Table 9. CO_2 production and heat output of wet wool after 24 hr at various temperatures (taken from, Rothbaum, H.P. 1961 J. Bacteriol. 81:165-171)*

Temp. °C	CO_2 production (g/sec-g dry wool x 10^8)	Heat output (cal/sec-g dry wool x 10^4)
26	18.5	11.0
37	33.0	15.0
50	14.7	4.2
60	17.5	6.0
70	16.4	3.4
74	9.2	1.7
78	0.8	0.0

---

*The entries representing 50°C through 78°C were used in developing Table 1.

penalty, based on the following lines of evidence; i) the heat output-temperature interaction and fixed temperature experimentation outlined in IIB; ii) the involvement of the genus Bacillus in composting, and the temperature relations of this group (39); iii) the field experience, exemplified by the examples developed in VA.

2. Temperature Control

In the Results section we emphasized control from the technical viewpoint of how closely pile temperature corresponded to the temperature controller set point. The observed pile temperatures are now reexamined in light of the suggestion that 60°C is the threshold to significant process deterioration. The reexamination involves the periods of operation under temperature feedback control. These periods, and summaries of the temperatures, are as follows: pile 4A, hrs 12 to 352, 1.8% of the values > 60°C; pile 4B, hrs 26 to 214, 58% of the values > 60°C; pile 4C, hrs 28 to 84, 100% of the values > 60°C. Thus according to our view of process control pile 4A was satisfactory, pile 4B was marginal, and pile 4C was unsatisfactory.

Any thermistor placement temperature set point combination is valid only for the particular pile size, configuration, concentration of readily available substrate, etc. This aspect of static pile composting deserves investigation. Meanwhile, a suitable combination for a particular set of circumstances can be found without great difficulty through experience.

C. EFFECT OF PILE TEMPERATURE ON pH, CO_2, AND MOISTURE CONTENT IN RUN 4

An adequate temperature control system was first available for run 4. The piles were controlled to approximate, in reference to the Fundamental Considerations, favorable (4A), intermediate (4B), and unfavorable (4C) temperatures. The effect of pile temperature on the indicated process parameters is now considered.

1. pH

In all of the piles the pH increased and then decreased. In pile 4A a secondary increase occurred, starting at approximately hr 380. The pH changes occurred most rapidly in pile 4A, followed by 4B and 4C. These general trends in pH are commonly observed in batch composting (18). The rapidity of their expression may be taken as an indication of the progress of the processing.

2. CO_2

a. The level of CO_2

The balance between production and removal determines the CO_2 content at any given time. Although the levels of CO_2 were generally similar in the three piles, it can be inferred that this reflected different circumstances, as follows. In pile 4A large amounts of CO_2 were produced and swept out by the strong ventilation. Conversely, in pile 4C both production and ventilation were slight. In pile 4B, an intermediate circumstance prevailed.

b. The supply of O_2

Judging from the relationship between CO_2 and O_2 (Fig. 14), at the point of sampling O_2 was generally within a few percent of the ambient value. In view of the argument developed in Section IIC2, it is considered that the supply of O_2 was nonlimiting with respect to biological activity. (But see'd'below.)

c. Link between temperature feedback and oxygenation

It is not accidental that an approach to process control based on temperature feedback, in conjunction with biologically favorable pile temperatures, provided an adequate supply of O_2. This is because pile temperature is a function of heat output and the heat, in turn, is generated through the biological consumption of O_2. Thus, although the blower responds directly to temperature, it responds indirectly to O_2 consumption. Pile 4A, but not 4B and 4C, was controlled to maximize O_2 consumption.

d. Possible misinterpretation of O_2 as a process parameter

Although high levels of O_2 in the composting mass are necessary for satisfactory operation, such levels are not necessarily indicative of satisfactory operation. Consider these contrasting sets of conditions: 1) biologically harsh temperature, low decomposition rate, weak ventilation, high O_2 level; 2) biologically favorable temperature, high decomposition rate, strong ventilation, high O_2 level. Sets 1 and 2 are exemplified by piles 4C and 4A, respectively. Although the O_2 levels are similar, conditions are otherwise dissimilar.

The O_2 level at any given time represents the balance between the rates of O_2 uptake and replenishment. In set 1 the rates of uptake and replenishment are both low, whereas in set 2 both rates are high. While the rate of O_2 uptake is related to microbial activity, the level of O_2 is not so related. Thus in isolation from other factors the level of O_2 cannot serve as a process parameter.

3. Moisture Content

The course of drying was similar in piles 4B and 4C in that the starting moisture content of 76% decreased to approximately 40% in 18 days. Drying was faster and more complete in pile 4A, in which a moisture content of 22% was reached in 15 days. Similarly rapid drying occurred in pile 5 during the first 120 hr, which is the period that it was controlled like pile 4A.

It may at first seem paradoxical that drying was faster at the lower temperatures. This result, however, is a logical consequence of the heat output-temperature interaction (Sec. II). This is because the removal of water through vaporization is a function of the amount of heat released microbially, which in turn is a function of the temperature of the microbial ecosystem. These relationships are developed further in the succeeding sections.

D. HEAT ANALYSIS

In this section the mechanisms of heat transfer are considered in relation to static pile composting. This permits a comparative estimation of the heat outputs in run 4. As noted previously, the observed course of drying can be satisfactorily explained, without further elaboration, in reference to the heat output-temperature interaction. Although the present analysis is not essential, it nicely illustrates the explanation in terms of a quantitative comparison of the heat outputs.

1. Steady State Heat Transfer Mechanisms

In this analysis a "black box" approach is taken in that only heat flow into and out of the pile as a whole is considered. This eliminates any need to consider heat flow within the pile. The calculations are based on pile 4A.

a. Radiant losses and gains

In estimating heat exchange radiation is generally considered to be negligible when the system's area is small, the operating temperature is mild, and the temperature differential is small. Although static pile composting fits this generalization, radiant gains and losses are nonetheless estimated.

Heat is lost from the pile through the emission of electromagnetic waves into the night sky. The governing relationship for such a phenomenon is an interpretation of the Stephan-Boltzman equation: Q rad = $\varepsilon \sigma A$ (T^4 high - T^4 low) where: Q rad = the radiant heat loss (Btu/hr)

$\sigma = 0.1713 \times 10^{-8}$ Btu/hr ft ^{2} $(^{o}R)^4$

A = surface area of the pile approx: 200 ft^2

T high = high temperature (^{o}R) approx 560^{o}R

T high = sky temperature (^{o}R) approx. 420^{o}R (average)

Therefore, assuming black body radiation (ε = 1.0) from the pile on a clear nigh

Q rad (out) = 23, 000 Btu/hr

During the daylight hours, however, there is an input of radiant energy from the sun. Based on tables of solar energy data (40),

Q rad (in) = 25,300 Btu/hr

The calculation thus shows a net gain of 2,300 Btu/hr, which is minor (see later). Moreover, since radiant gains and losses are at the pile surface, which consists of the cover material, it is unlikely that the composting material itself is significantly heated or cooled by radiant effects. Radiation is omitted from further consideration.

b. Conduction

Heat is conducted from the composting mass to the woodchip base, and then to the concrete pad and underlying earth. Likewise, there is conduction to the woodchip cover. The conservative assumption is made that woodchips act as solid wood (k = 0.05 Btu/hr ft ^{o}F) with respect to insulating properties. The concrete pad and ground are omitted from consideration. The governing relationship is as follows:

Conducting heat flow

$$Q_{cond} = \frac{kA}{L} \text{ (T high - T low)}$$

(A homogeneous conducting material is assumed.)
where:

k = thermal conductivity of the wood = (0.05 Btu/hr ft ^{o}F)

A = area of base and cover = (371.6 ft^2)

L = thickness of woodchip base (0.5 ft)

T high = pile temperature (130^{o}F)

T low = average exterior temperature (67^{o}F)

Therefore,

$$Q_{cond} = \frac{(0.05)\ (371.6)\ (63)}{0.5} \quad \frac{13\ \text{Btu}}{\text{hr}} = 2300 \text{ Btu/hr}$$

c. Vaporization and convection

Air passing through composting material increases in temperature and humidity, removing heat and water from the pile in the exhaust stream. Two mechanisms are involved: vaporization (the phase change of water from liquid to gas) and dry convection (the heating of dry air). Both mechanisms are dependent on ventilation.

The losses are estimated for the quasi-steady state, as represented by the period of operation at the temperature set point.

Basic Assumptions

Input conditions:

60% relative humidity

60^{o}F

Air flow (to maintain steady state temperature in 7 ton pile):

1 inch H_2O static pressure across Dayton 1/3 hp blower.

$\dot{V} = 530 \frac{ft^3}{min}$ (volumetric air flow from Dayton performance curve)

Blower is on for 75% of time

Output conditions:

100% relative humidity

130°F

Air Mass Flow Calculations

$$m = \dot{V}\,\rho\,(\text{duration})$$

$$\dot{V} = 530\ \frac{ft^3}{min}$$

$$\rho = 0.075\ \frac{lb}{ft^3} @\ 60^\circ F$$

duration = 0.75 (fractional "on time")

$$m = (530)\,(0.075)\,(0.75)\frac{lb}{min} \times \frac{60\ min}{hr} = 1788\ \frac{lb}{hr}$$

Convective Heat Flow

$$Q_{convection} = m\,(h_{out} - h_{in})$$

$h_{out} = 155\ \frac{Btu}{lb_{dry\ air}}$ (enthalpy of exit air)

$h_{in} = 22\ \frac{Btu}{lb_{dry\ air}}$ (enthalpy of inlet air)

$$Q_{convection} = 1788\,(155-22) = 237{,}804\ \frac{Btu}{hr}$$

Dry air fraction of $Q_{convection}$

$$Q\ air = m\ Cpo\ \Delta T$$

$Cpo = 0.24\ \frac{Btu}{lb\ ^\circ F}$ (specific heat of air)

$$\Delta\ T = 70^\circ F$$

$$Q\ air = (1590)\,(0.24)\,(70)\ \frac{Btu}{hr}$$

$Q\ air = 26{,}712\ \frac{Btu}{hr} = 11\%$ of $Q_{convection}$

Vapor fraction of $Q_{convection}$

$$Q_{vapor} = Q_{convection} - Q_{air}$$

$Q_{vapor} = 211{,}092 \frac{Btu}{hr} = 89\%$ convection

Therefore the rate of heat loss from the pile can be expressed as follows:

$$Q_{total} = Q_{vaporization}\ (88\%) + Q_{dry\ air}\ (10\%) + Q_{conduction}\ (2\%)$$

1. Transient Heat Outputs in Run 4

As noted previously, it is assumed for purposes of these calculations that the air existing from the piles was saturated with water (100% RH). The assumption was considered to be valid as long as the moisture content of the mass was >50%. Therefore, the present calculation was terminated at hr 120.

a. Procedure

As noted in V D1, the steady state heat transfer from the pile was in the form of conduction, convection, and evaporation. In the transient condition the pile changes in temperature (heat content), making it necessary to modify the "black box" approach used in the steady state analysis. To better estimate the microbial heat output during the initial 120 hours, consideration must be given to the heat released from the microbes to the sludge-woodchip mass. This factor of heat transfer is given in the form of

$$Q_{\Delta T} = \frac{MC\Delta T}{\Delta t}$$

where

M = sludge-woodchip mass - 14,000 lb

C = specific heat of the mass

(Conservatively assumed to be $C_{water} = 1.0$ Btu/lb ^{o}F)

ΔT = change of average probe temperature

Δt = Time interval

The resulting equation is a combination of the above relationship with the relationships already noted for conduction and total convection. Therefore the analysis progress as follows:

$$Q\ total = Q\ convection + Q\ conduction + Q\ \Delta T$$

where

i. $Q\ \Delta T = \frac{(1400)\ (1)}{4}\ (\bar{T}_t - \bar{T}_{t-4})$ Btu/hr

- $\bar{T}$ is an average value of the 14 probe temperatures @ time t.
- Equation includes adjustment for four hour intervals between temperature readings.

ii. Q convection = m $(h_{out} - h_{in})$

- The equation is based on the variable ambient temperature as well as the assumptions noted in section V D1.
- The value for h_{out} is represented by T_{out}, which was estimated as follows. Firstly, it is considered that, per unit surface area, more air exits from near the top of the pile than near the base. Secondly, the surface area near the base is greater than that near the peak. Taking these factors into account, the following numerical coefficients were assigned:

  $\bar{T}_{out} = 0.1\ (T_5) + 0.2\ (T_9) + 0.2\ (T_{12}) = 0.25\ (T_{13}) + 0.25\ (T_{14})$, where the numerical subscripts refer to the probe positions. As compared to an unweighted average temperature, this procedure gives a relative advantage to the hotter piles.

iii. Q conduction $= \frac{0.05\ (371.6)}{0.5}\ (\bar{T}_t - 67)$ Btu/hr

Based on the same value for $\bar{T}_t$ that was noted in the $Q\ \Delta T$ calculations.

A sample calculation for transient heat output is provided in the References and Notes Section (41).

b. The estimates

Heat output was greatest in pile 4A, intermediate in pile 4B, and least in pile 4C (Fig. 129). This constitutes a field scale demonstration of the heat output-temperature interaction.

For comparative purposes the highest output for pile 4A (418 x 10^3 Btu/pile, at hr 100) was expressed as cal/sec-g. The calculation is based on a pile weight of 14,000 lb and a moisture content of 52%. It results in a value for heat output approximately 6X that reported for straw and 10 - 20X that for wool (Table 10). The comparison is tentative as the experimental scale (field scale for the sludge, and laboratory scale for the straw and wool), and the means of calculations, differed greatly. Although comparison to values in the literature is of interest, the heat analysis was mainly for comparison among piles 4A, 4B and 4C.

E. INTERRELATIONSHIPS AMONG HEAT OUTPUT, TEMPERATURE, AND WATER REMOVAL

Given that evaporative cooling is the main mechanism of heat removal, the observation that the cooler pile (4A) dried faster than the hotter ones (4B and 4C) can be explained. The removal of water from the composting mass cannot be understood in terms of temperature alone but, in addition, the unique interaction between biological heat output and temperature must also be considered. The overriding issue is the sustainability of evaporative cooling, as outlined below in general and specific explanations.

1. General Explanation

From the equation for total convection: Q total = m ($h_{out} - h_{in}$), it is seen that a given amount of heat can be removed (Q total) with various combinations of air mass flow (m) and enthalpy differential ($h_{out} - h_{in}$). If no reference is made to the microbial ecosystem it might seem that Q can be maximized by increasing m or by increasing h_{out} (pile temperature). Because of its adverse effect on heat output, however, a high value of h_{out} is sustainable only if m is correspondingly low. In contrast if h_{out} is maintained within a biologically favorable range not only is a high value of m sustainable, it is required to prevent an undue temperature ascent. In reality only m can be maximized, and this is accomplished by adjusting h_{out} to favor ecosystem activity. Therefore, since most of the heat is removed through vaporization, more water is removed at the lower, biologically favorable, pile temperatures.

2. Specific Explanation

In pile 4C biological heat output was slight at the high temperatures.

Table 10. Microbial heat output at comparable temperatures in different materials

Material	Experimental arrangement	Temperature °C	Heat output cal/sec-g(dry wt)	Source
Straw	Adiabatic apparatus	~60	0.0015	Ref. & notes 14
Wool	Adiabatic apparatus	~55	0.0008	Ref. & notes 16
Wool	Fixed temperature	50	0.0004	Ref. & notes 24
Wool	Fixed temperature	60	0.0006	Ref. & notes 24
Sewage sludge	Field scale static pile (4A)	~50	0.0088	Present report

Consequently, the temperature was not sustainable even in the face of the relatively weak ventilation scheduled by timer. Therefore, there was little opportunity for evaporative cooling.

Heat output in pile 4A, in contrast, was vigorous. Consequently, extensive blower "on" time was required to prevent an undue temperature ascent. Blower "on" time, in conjunction with the temperature feedback control system, represents opportunity for evaporative cooling.

F. WATER REMOVAL AND DRYING AS INDICATORS OF ORGANIC MATTER DECOMPOSITION

Given that:

i. Water removal is mainly through evaporative cooling, and

ii. Evaporative cooling is driven by microbial heat output at the expense of organic matter, it follows that:

iii. The rate of water removal is indicative of the rate of organic matter decomposition. The rate of decomposition is underestimated through water removal, however, because some heat is dissipated through mechanisms other than vaporization.

Water removal is not usually measured in field practice, but rather the moisture content is determined. The tendency to dry (as determined through moisture content) is partially offset by the production of water metabolically (see IID3). Consequently, drying is a more conservative indicator of organic matter decomposition than water removal.

G. INTERACTION BETWEEN HEAT OUTPUT AND MOISTURE CONTENT

If the process is controlled through temperature feedback and, as in pile 4A, biologically favorable temperatures are maintained, drying is promoted. This brings into play an interaction between heat output and moisture content, as follows. Heat output causes drying, eventually to the point that biological activity suffers from the lack of water. In turn this decreases heat output. Finally, heat output and drying essentially terminate.

The threshold to moisture limitation is poorly defined, and undoubtedly differs according to the nature of the material. At present the only general conclusion possible is that a moisture content of 50% supports vigorous activity (II D2). Regardless, it was demonstrated that in piles self-limited through drying the activity was renewed with the addition of water from an outside source.

Thus, the composting ecosystem first tends to self-limit through the excessive accumulation of heat (the heat output-temperature interaction). If this is averted through judicious heat removal, then the tendency is to self-limit through the dissipation of the water. That is, the heat output-moisture content interaction comes into play.

H. COMPARISON OF DRYING IN PILES 4A AND 5

For the first 120 hrs of these runs, piles 4A and 5 had identical set points (45°C), and comparable blower demands and temperatures. Similarly, during this period the moisture contents decreased by 25% and 27%, respectively. Pile 5 was subsequently subject to several control changes. Regardless, at hr 160 the blowers were turned on manually to give 100% "on" time. Whereas in pile 4A, which remained under temperature feedback control, the moisture content continued to decline, in pile 5 it stabilized at around 40%. Thus, more ventilation resulted in less drying.

This seemingly paradoxical behavior is satisfactorily explained in terms of the heat output-temperature interaction, as follows. At hr 160, when the blowers were turned on manually, the ecosystem was unable to replace the extensive heat losses. Judging from the results of the "rewet" experiment, this was because the moisture content was restrictive of biological activity. Consequently, the temperature declined abruptly--"stranding" the thermophilic population. Although a large volume of air passed through the pile, its capacity to remove water did not benefit from biological heat output and the associated demand for evaporative cooling.

I. FUNDAMENTAL DISTINCTION BETWEEN COMPOSTING SYSTEMS: THE RETENTION OR REMOVAL OF METABOLIC WASTE HEAT

Based on these considerations, we postulate that, fundamentally, there are two kinds of composting systems: those that retain, and those that remove, waste heat. Since heat removal is mainly through evaporative cooling, retaining and removal also refer to water. The attributes of these systems are summarized in a series of equivalencies.

Waste heat retaining ≡ inhibitively high temperatures ≡ debilitated community ≡ slight heat output ≡ slight water removal.

Waste heat removing ≡ favorable temperature ≡ robust community ≡ substantial heat output ≡ substantial water removal.

In the first system, the heat output - temperature interaction is allowed free rein, resulting in a self-debilitated community and slight heat output. The peak temperatures are sustainable only if ventilation is slight, and thus there is little opportunity for water removal. This condition is a consequence of viewing ventilation as a means of supplying O_2, to the exclusion of its heat removal function (see 6, 9, 10). With more ventilation the temperature retreats, as exemplified by pile 1C, and to a lesser extent pile 4C. Again, there is little opportunity for water removal. Furthermore, the sudden decrease from harsh to benign temperatures results in only a slow recovery of the community. This is because the peak temperatures "partially sterilize" the material.

In the second system the temperature ascent is arrested through heat removal so as to maintain the temperature in a biologically favorable range, thereby sustaining vigorous heat output and water removal. Although control is directly through temperature, indirectly it is based on heat output and O_2 uptake. Consequently, even though the O_2 uptake is great, the pile is well oxygenated. Controlled in this manner the ecosystem tends to self-limit through drying, eventually becoming inactive at some limiting moisture content. Alternatively, if water is added from an outside source microbial activity is prolonged, yielding a more highly stabilized end product. Of course, less end product results (on a dry weight basis).

J. THE "RUTGERS - USEPA - NJDEP - CCMUA STATIC PILE COMPOSTING PROCESS"

The waste heat removing approach to composting is based on the interplay between biological and physical factors, as expressed through the integrated control of heat output, temperature, ventilation, and water removal. This approach was approximated in pile 4A, and for part of the run in pile 5. The new process is called the "Rutgers-USEPA-NJDEP-CCMUA static pile composting process".

The waste heat removing principle can be applied through process designs other than that of static pile.

In fact, at least one continuous composting process is capable of operation in the waste heat removing mode (42). Batch composting by the mechanically agitated windraw method probably tends to operate at some point intermediate between the retaining and removing modes (43). The Beltsville-USDA static pile composting process is a waste heat retaining system.

It is relevant to compare the two approaches to static pile composting. The duration of the "active stage" in the Beltsville process is fixed at 21 days regardless of the characteristics of the sludge, even for materials as disparate as raw sludge and anaerobically digested sludge. A subsequent curing stage lasts for 60 days. In contrast, the duration of the temperature feedback control stage of the Rutgers process depends on the oxygen demand and water content of the starting material, in conjunction with deliberately selected waste treatment objectives. This brings into focus the question of specific "curing" objectives, and indeed whether a curing stage is needed.

VI. The Fundamental Basis of the Rutgers USEPA-NJDEP-CCMUA Sewage Sludge Static Pile Composting Process from Heat Flow Considerations

A. Introduction

The fundamental basis of the Rutgers USEPA-NJDEP-CCMUA Sewage Sludge Static Pile Composting Process, hereafter refered to as the Rutgers Static Pile Composting Process is the controlled ventilation of waste heat to maintain a pre-set microbially favorable composting temperature that will result in a maximal rate of heat production and consequent moisture loss (drying). Once biologically favorable temperatures are established, the similarities and differences of the Rutgers Static Pile Composting Process to other unconfined composting processes (i.e. windrow and aerated static pile) are essentially related to the heat flow of each respective system. Consequently, in order to fully define the basic tennents of the Rutgers Static Pile Composting Process sewage sludge composting must be examined in light of the heat flow considerations of the process.

Sewage sludge composting is the aerobic thermophilic decomposition of organic constituents to a relatively stable humus like material (1). In terms of energy conversion, this can be viewed at the aerobic biochemical conversion of stored energy in the form of organic constituents to ultimate energy forms expressed as carbon dioxide, water, biomass, stabilized and products and heat. Environmental factors such as the volatility and type of material, mositure content, oxygen concentration, nutritional requirements, pH and temperature affect the rate and product of the process (2). Thus in relationship to other familiar aerobic biological treatment systems utilized in waste treatment it is similar both in its process requirements and objectives (i.e. the controlled biological stabilization of organic matter).

Composting is dissimilar in that the process exploits the heat generated in decomposition. Sewage sludge composting processes self heat as evidenced by spontaneous temperature increases that occur during the course of the process, as a result of the insulating properties of the assembled mass. Thus thermophilic temperatures can be self sustained for the decomposition of organic matter, provided that microbial populations, environmental factors and insulating properties are maintained. (3)

It is this self heating phenomenon of sewage sludge composting relative to the flow of heat within the composting mass that is the focus of the discussion that follows. Although all sewage sludge composting produces share the same fundamental process requirements of

- ·Bulking agents for porosity and moisture
- ·Nutrition and moisture
- ·Optimum temperature (55-65°C) (4),

they are unique with regard to the control of self generated heat, which is the basis of the Rutgers Static Pile Composting Process.

B. Conceptual Development of Heat Flow

The heat generated by the aerobic biological stabilization of organic matter through composting is ultimately expressed in the form of stored heat (conduction to the composting mass) and expended heat (losses expressed through conduction to surfaces in contact with the composting mass, vaporization and convection to the atmosphere). Thus, a general expression for the mass rate flow of microbial heat generated by composting can be expressed as follows:

Q_m	=	Q_s	=	Q_e (eg 1.)
Mass rate of microbially producted heat	Conduction convection vaporization	Mass rate of heat stored		Mass rate of heat expended

Where:

Mass Rate of Heat Stored - Q_s

$$Q_s = q_s + q_w \quad . . . \text{(eq 1.1)}$$

where: q_s = mass rate of heat stored by dry solids
q_w = mass rate of heat stored by resident water

Mass Rate of Heat Stored by Dry Solids - q_s

$$q_s = M_s C_s \frac{\partial T}{\partial X} \quad . . . \text{(eq 1.1a)}$$

where: M_s = mass of dry solids
C_s = specific heat of dry solids
$\frac{\partial T}{\partial X}$ = temperature gradient

Mass Rate of Heat Stored by Resident Water - q_w

$$q_w = M_w C_w \frac{\partial T}{\partial X} \quad . . . \text{(eq 1.1b)}$$

where: M_w = mass of water
C_w = specific heat of water

Mass Rate of Heat Expended - Q_e

$$Q_e = q_a + q_v + q_c \quad . . . \text{(eq 1.2)}$$

Where: q_a = mass rate of heat loss to the atmosphere by convection
q_v = mass rate of heat loss to the atmosphere by vaporization
q_c = mass rate of heat loss to surface in contact with the composting mass by conduction

Mass Rate of Heat Expended by Convection - q_a

$$q_a = h_a A \Delta T \quad . . . \text{(eq 1.2a)}$$

where: h_a = heat transfer coefficient of dry air
A = area perpendicular to flow
ΔT = temperature differential between air and composting mass

Mass Rate of Heat Expended by Vaporization - q_v

$$q_v = h_v A \Delta T \quad . . . \text{(eq 1.2b)}$$

where: h_v = heat transfer coefficient of water vapor

Mass Rate of Heat Expended by Conduction - q_c

$$q_c = KA \frac{\Delta T}{\Delta X} \quad . . . \text{(eq 1.2c)}$$

where: K = thermal conductivity of contact
A = area of contact
$\frac{\Delta T}{\Delta X}$ = temperature gradient

If we can assume that radient heat gains are small and approximately equal to radiant heat losses,

then:

$$Q_m = (q_s + q_w) + (q_a + q_v + q_c) \quad . . . \text{(eq 2.)}$$

Thus, the heat flow of a composting mass can be represented by equation 2.

Utilizing this description of the general heat flow of microbially produced heat in a composting mass, an expression of the self heating phenomenon as defined by spontaneous temperature rise in the composting mass can be provided for the unconfined composting processes of windrow and static pile sewage sludge composting.

C. Windrow Composting Heat Flow

In windrow composting a mixture of bulking agent and dewatered sewage sludge is stacked in long parallel rows or windrows. The cross section may be triangular or trapezoidal in shape, depending upon the characteristics of the equipment utilized for mixing and turnover of the piles. The width is typically 15 feet (4.5m) and the height varies from 3 to 7 feet (1 to 2m). (4)

Convective air movement within windrows is essential for providing oxygen for the microbial ecosystem of the piles. Microbially produced heat generated in the piles warms the resident air causing it to rise, producing a natural chimney effect. The rate of aeration of the pile is controlled by the porosity and size of the windrow and the period mechanical turning of the windrow.

Temperature in the windrows can rise to a maximum at the central portion of the pile of 65°C with operating temperatures maintained at 60°C(3) as a result of microbial heat production. A heat flow model of the system can be expressed through three phases typically experienced in a windrow composting system, utilizing equation 2.

Phase I - Self heating mass characterized by $Q_m > (q_a + q_v + q_c)$
Q_m-maximized

Phase II - Temperature maintenance characterized by
$Q_m = (q_a + q_v + q_c)$, Q_m-minimized

Phase III - Mechanical turnover (aeration) characterized by
$Q_m < (q_a + q_v + q_c)$, (q_a, q_v, qc) maximized

During Phase I, microbial heat production is stored through heat flow to the solids and water of the mass. The rate of heat production (Q_m) exceeds the rate of heat expended ($q_a+q_v+q_c$). The characteristic stored heat effect is expressed through spontaneous temperature increases. At some elapsed time from the initiation of Phase I, the windrow experiences a steadying of temperature as is expressed by Phase II. Microbial heat production is not stored since the rate of heat expended by the system equals the rate of production ($Q_m = q_a+q_v+q_c$). Phase III, mechanical turnover of the pile, results in the rate of expended heat exceeding the rate of heat production as a consequence of an infinite increase in the exposure of surface area to the ambient air temperature, resulting in rapid conductive and convective heat losses. The characteristic effect is a sudden temperature decline of the pile as the rate of expended heat exceeds the rate of microbial heat production resulting in negative storage. However, once turnover has been completed and the windrow sufficiently aerated and mixed, sudden heat losses are terminated and the cycle begins again at Phase I.

Generally, the requisite condition to initiate mechanical turnover is insufficient aeration of the composting mass by natural convection, as expressed through a steadying or decline in pile temperature. Turnover provides aeration of the mass in support of the microbial ecosystem, while producing heat losses that result in the reestablishment of Phase I conditions. Since the maximization of heat production is concomitant with stabilization, the rate composting is thus hastened.

It is not surprising that the Los Angeles County Sanitation District practices windrow pile turnover as frequently as 2-3 times a day during the initial 5 or 6 days of the windrow composting of digested sludges, thereafter turnover occurs at a rate of at least once each day. (4) Turnover not only facilitates aeration of the mass, but promotes the reestablishment of Phase I conditions through heat loss.

D. Aerated Static Pile Composting Heat Flow

The aerated static pile composting process was developed to reduce the land requirements and problems associated with windrow composting and provide for the composting of raw sewage sludge. The system is characterized by large trapezoidal shaped piles consisting of 40-50 tons of bulking agent and sludge with an insulating cover, assisted in aeration by forced vacuum induced ventilation. (5)

The aerated static pile composting process can also be represented by the general expression of heat flow of equation 2 through the model phases of the process.

Phase I - Self heating mass characterized by $Q_m > (q_a + q_v + q_c)$
Q_m-maximized

Phase II - Temperature maintenance characterized by
$Q_m = (q_a + q_v + q_c)$, Q_m-minimized

In static pile composting, the pile self heats in Phase I ventilated by natural convective updraft and counter current forced vacuum induced ventilation to aid aeration of the pile. The rate of blower induced forced vacuum ventilation is fixed being sufficient to support aerobic microbial activity and thus negating the need for pile turnover for aeration.

In a pattern similar to the initial ascent of temperature of the windrow composting system, static pile temperatures elevate to a maximum range of 70-80°C. The temperature being a function of the greater assembled mass and the application of an insulating cover to retain heat. The maintenance of temperature characteristic of Phase II is a result of microbial heat production equalling the rate of heat expended. However, by design the rate of heat expended (q_a+q_v+q_c) is minimized through an insulating cover that reduces q_c and a fixed ventilation rate that just provides sufficient pile aeration without excess heat loss through convection (q_a+q_v). Unlike windrow composting, turnover is not necessary for aeration. However, Phase I conditions are not reestablished in the system. Thus, if the rate of heat expended is minimized by design, the rate of microbial heat production is also minimized during Phase II.

As a consequence of process design, q_a+q_v+q_c are minimized to faciliate rapid self heating. Similar conditions must prevail in Phase II of the process since the forced vacuum ventilation rate is fixed throughout the process. Thus, the stabilization of temperature is a result of a decline in the rate of heat production. However, if the rate of heat production is minimized, the concomitant rate of stabilization is also minimized. The model indicates that sustained pile temperatures of 70-80°C during Phase II are not indicative of maximized rates of heat production, rather they reflect the efficiencies of insulation provided by and to the pile mass.

E. Rutgers-USEPA-NJDEP-CCMUA Sewage Sludge Static Pile Composting Process Heat Flow

Unlike the fixed rate forced vacuum induced ventilation static pile composting process, forced ventilation has a dual purpose in the Rutgers Static Pile Composting Process. The first purpose is to provide sufficient aeration to maintain favorable oxygen concentrations in the mass in support of aerobic microbial activity. The second purpose is to provide sufficient ventilation of the pile mass to remove waste heat and maintain optimal temperatures that result in a maximized rate of heat production and consequent rate of stabilization.

In terms of equation 2 the Rutgers Static Pile Composting Process can be characterized as follows:

Phase I - Self heating mass characterized by $Q_m > q_a + q_v + q_c$
Q_m-maximized

Phase II - Temperature maintenance characterized by
$Q_m = q_a + q_v + q_c$, Q_m-maximized
$(q_a$ & $q_v)$-maximized

During Phase I of the process, the rate of heat expended by the system is minimized through an insulating cover and a rate of forced ventilation that supports aerobic conditions of microbial activity. The resultant effect being a spontaneous temperature ascent. However, unlike the fixed rate forced vacuum ventilated static pile composting system, Phase II is not the result of an attenuation of the rate of heat production to meet the fixed rate of heat expended from the system. It is the result of an increase of the rate of heat expended to remove waste heat and establish conditions similar to Phase I where the rate of heat production is maximized. This is accomplished by increasing the rate of pile ventilation of waste heat to keep pace with the rate of heat production, to maintain a preset temperature which is optimal for microbial activity. The removal of waste heat is similar in effect to the removal of heat through turnover in windrow composting. The exception is that the rate of heat removal is controlled and matched to heat production, thus eliminating sudden stored heat losses.

The model predicts that if the rate of microbial heat production is maximized, the rate of expended heat will be maximized by vaporization (q_v) and convection q_a to the air, through maximized rates of ventilation. Estimates of the potential heat losses by both mechanisms indicate that approximately 85% of the heat loss will occur through vaporization (q_v, evporative cooling), while only 12% will occur through convection to dry air. Thus, if vaporization (evaporative cooling) is the principle mechanism of cooling, the rate of moisture loss of the pile should be maximized at the maximum rate of microbial heat production.

The Rutgers Static Pile Composting Process promotes drying of the composting mass through evaporative cooling, driven by microbial heat production. Furthermore, heat loss proceeds until pile moisture becomes limiting to the microbial ecosystem (i.e., the pile dries). Finally, the maximum rate of moisture loss defines the maximum rate of microbial heat production and consequent stabilization.

F. The Effect of Natural Convective Updraft in Static Pile Composting

Natural convective updraft is an essential element of static pile composting ventilation. The resident air in composting piles, warmed by the microbially produced heat, rises due to density differences, producing a natural chimney effect, aided by the trapazoidal shape of the piles (4). This natural convective updraft ventilation provides a mechanism for heat removal and gas exchange in support of the composting process.

The development of the mechanically aerated static pile composting process for sewage sludge is based upon providing void space to the sludge by bulking agent addition for pile ventilation and a vacuum induced ventilation pattern to insure sufficient gas transfer to maintain the aerobic thermophilic decomposition environment of the composting process (5). The vacuum induced mechanically aerated static pile composting process is not designed for the removal of heat from the pile, indeed all efforts are aimed at minimizing heat loss to attain temperatures in excess of 65°C. Consequently, fixed mechanical ventilation sequences provide for only 25% of a ventilation cycle (4 min. out of 20 min.) for mechanically induced vacuum ventilation, with the remaining period of the cycle left to the ventilation effect of the natural convective updraft of the piles. This is demonstrated in Run #1 of the experimental data (see IV Results and Technical Evaluation p. 21).

1. Run #1

The pilot scale piles of Run #1 were approximately 1/7th the size of the standard vacuum induced mechanically aerated piles (53 tons) (5), ventilated mechanically by vacuum induced aeration with a blower and hose system equivalent to the recommended standard pile for vacuum induced mechanically aerated piles (5). Pile 1A had a 3.3% mechanical ventilation on time per cycle while piles 1B and 1C had 13.3 and 100%, respectively. A review of the temperature profiles of the probes in each pile during the run provides insight into the pattern of ventilation of the piles.

The temperature vs time profiles of the temperature monitoring probes of pile 1A (Fig. 15, 16 & 17; VIII) indicate that probe #1 located in the apex of the pile configuration (see Figure 15; VIII) was consistantly higher in temperature than probe 5 located at the bottom center of the pile. Additionally, probe 3 was consistantly cooler than probe 4, 5, and 1, while probe 4 was generally cooler than probes 5 and 1. The temperature patten appears to indicate a natural convective updraft pattern with higher temperatures at the apex of the pile (probe 1) and cooler temperatures toward the base of the pile (probe 5). The difference in profile pattern of probes 3 and 4 may indicate the effect of the blower ventilation since probe 3 was closest to the blower and lower in temperature profile.

A similar pattern of temperature profile is evident in pile 1B (Fig. 18, 19, and 20; VIII) where the temperature profile of probe 1 is higher than probe 2 which is higher than probe 5. This again indicates a predominant temperature rise with height in the pile as would be expected by natural convective updraft ventilation. Probes 3 and 4 confirm the uneven distribution of vacuum induced ventilation with lower temperatures recorded for probe 3 closest to the blower than probe 4 which was further from the blower. This latter effect was most probably the result of the failure to bury the ventilation hosing for all piles of Run #1 in the woodchip base to distribute the vacuum draw to the pile.

Pile 1C provides the most revealing information relative to the effect of natural convective updraft ventilation. Ventilated continuously in a vacuum induced (draw) fashion, during the initial 170 hrs, a natural convective updraft ventilation pattern of probe 1 temperatures generally exceeding probe 2, generally exceeding probe 5 is evident, even though mechanical ventilation was countercurrent (vacuum) and continuous (Fig. 21, 23; VIII). In consideration of the fact that the blower size utilized was equivalent to the recommended size to be utilized for an aerated static pile of more than 7 times the weight and size of the pilot scale pile of run #1 it is evident that the principle pattern of ventilation is an updraft pattern exiting through the apex of the pile. If the ventilation pattern was consistent with the mechanically induced vacuum draw the pattern would have been reversed.

Based on these observations it appears that despite of continuous mechanical vacuum induced ventilation (draw), the predominant pattern is a natural convective updraft through the apex of the pile. The mechanically induced vacuum ventilation failed to overcome the natural convective updraft pattern of the pilot scale pile, thus introducing serious doubt as to the ability of such a pattern of ventilation to adequately control the ventilation pattern of larger scale piles, at an intermittent sequence of mechanically induced ventilation.

2. Run #2

Run #2 was conducted to investigate a mechanically induced ventilation pattern that could assist the natural convective updraft patterns observed from Run #1. Consequently, three pilot scale piles were constructed, two of which were provided with continuous mechanically induced ventilation of divergent patterns and one provided with no mechanical ventilation (see Table 4, Sec. IV page 25). A review of Figures 29-30 of Sec. VIII indicates similar patterns for similarly placed probes for the passively ventilated (non mechanically induced ventilation) pile 2A and the mechanically induced vacuum ventilated pile 2B. In contrast the mechanically induced pressure ventilated pile 1C indicates an increase in the pattern of ventilation with lowest temperatures registered at the base of the pile (probe 5I, Fig. 33, VIII) and increasing temperature profiles towards the apex of the pile (probe 1I, Fig. 31, VIII). Apex temperatures registered almost 20°C difference for pile 2C than piles 2A and 2B.

The data indicates that a mechanically induced ventilation pattern in concert with the natural convective updraft (pressure ventilation) can assist and control pile ventilation, while a mechanically induced ventilation pattern countercurrent to the natural convective updraft must be sufficient to overcome the natural convective updraft ventilation pattern of the pile. It would appear for the blower and pile sizes tested in Run #2 that mechanically induced ventilation patterns in concert with the natural convective updraft (pressure) are more effective at ventilation control than countercurrent patterns (vacuum).

The implication of these observations is that pile ventilation can be controlled for static pile composting, thus providing the opportunity to ventilate waste heat to control pile temperature through mechanically induced forced pressure ventilation in concert with the natural convective updraft pattern of the pile. Command of pile ventilation to control pile temperature thus provides for more complete control of the process and the potential for optimization. The succeeding test runs were conducted with mechanically induced forced pressure ventilation in concert with the convective updraft pattern of the pile with temperature control to optimize the process.

G. Evaporative Cooling and Moisture Loss in Static Pile Composting

The natural convective updraft of static pile composting provides for gas transfer and heat loss through convection. Convective heat loss is facilitated by evaporative cooling (vaporization) and dry air convection. Evaporative cooling is estimated to provide approximately 85% of the heat loss with 12% attributable to dry air convection. The principle mechanism for temperature control through controlled pile ventilation is evaporative cooling.

As the interior air in the void spaces of the pile warms, due to the microbially produced heat, its water holding capacity increases, providing a mechanism for heat removal. The moisture ladden warm air rises through the pile. Evidence of this phenomenon is often observed as visable exit vapors, when the warm moisture ladden air leaves the pile and condenses in the ambient atmosphere around the pile. Convective updraft thus provides a natural mechanism for the removal of waste heat from the composting process through evaporative cooling,resulting in moisture loss (drying) of the pile.

Mechanically induced ventilation patterns which augment the natural convective updraft pattern will increase the rate of gas transfer and convective heat losses. The consequence is an increased rate of moisture loss, provided the principle mechanism of heat loss, evaporative cooling, does not exceed microbial heat production, resulting in a cooling of the pile and reduction of the water holding capacity of the interior pile air. Therefore, at a set pile temperature range, the rate of microbial heat production would require an equivalent rate of heat loss through convection for temperature maintainence. Any imbalance between the rates of microbial heat production and convective heat loss would result in heat storage (pile temperature rise) or heat loss (pile temperature fall) provided that conduction losses are minimized through efforts of pile insulation.

Therefore, if a balance is established between microbial heat production and convective heat loss, a rate of pile moisture loss (drying) is defined for a set pile temperature. Consequently, the maximal rate of pile moisture loss would approximate the maximal rate of microbial heat production and define the temperature optimum of the process.

Maintainence of a set pile temperature requires the establishment of a balance between microbial heat production and convective heat loss. Control of the rate of microbial heat production requires control of microbial activity through environmental factors (i.e. pH, nutrient, substrate, etc.) which could affect the product of the process. Control of convective heat loss, however, requires control of the rate of evaporative cooling through pile ventilation and temperature both of which are controllable factors through forced pressure ventilation as demonstrated by Run #2 pile 2C.

Runs #3,4, & 5 were thus designed to evaluate the performance of various compost pile temperature ranges with mechanically induced forced pressure ventilation controlled by a thermistor set in the pile that actuated the blower when the set temperature was exceeded.

1. Run #3

As indicated in Table 5 (p. 28) three piles (3A, B and C were constructed with temperature set points of 55°, 65° and 75°C respectively. A mechanical forced pressure ventilation pattern was established to provide timed intervals of ventilation for pile aeration until the set point temperature was achieved, then to automatically switch to temperature demand ventilation to maintain the set point temperature. The initial timed cycle was increased at 40 hrs. into the run, as indicated by Table 5 (p. 28), due to the failure of all piles to self heat, which was suspected to be a failure of sufficient ventilation.

Blower duration was monitored in the piles as well as temperature, pH, and moisture content over the run length. The figures of blower duration vs. time (Fig. 45-47 VIII) indicate a greater demand for ventilation of pile 3A when compared to pile 3B, as would be expected from the lower set point temperature of pile 3A (55°). Pile 3C failed to reach the set point temperature and did not go to temperature demand ventilation.

A review of the interior temperature probes of piles 3A, B and C (Fig. 48-55 VIII) indicate that pile 3A and 3B temperatures near the thermistor were well below the set point (probe 2, 3, 4, and 5) although pile 3B temperatures for probe 5 were at or near the set point. Pile 3C failed to reach the set point temperature.

Moisture loss over the run was not significant and variation was observed between core and parameter samples (Fig. 68, VIII). The test was repeated with modifications to the placement of flexhose and shielding of the thermistor to prevent localized temperature response.

2. Run #4

A run similar in pattern to Run #3 was repeated for Run #4. Modifications were made to investigate three temperature set points of 45°, 55° and 65°C. Additionally the timed cycle sequence was increased in ventilation rate to insure aeration of the piles (see Table 6 p. 30).

Temperature demand ventilation was actuated for all three temperature set points (Fig. 70-72, VIII). As indicated by the graphs of temperature for the probes in each pile (Fig. 73-92, VIII), temperature was reasonably maintained in each pile during the initial 250 hrs. for all piles. Most importantly, moisture content during the run (Fig. 96) indicated a significant increase in the rate of drying of pile 4A (45°C set point; 45-60° range).

Pile 4A dryed to 22% moisture in 360 hrs. as compared to approximately 45% moisture for piles 4B and C. The blower demand curve (Fig. 40, VIII) indicated a progressive decrease of forced pressure ventilation beyond 150 hrs, which was interpreted to be the result of reduced microbial activity from the drying of the pile.

3. Run #5

A fifth run was made utilizing a larger pile configuration at the 45°C set point temperature (see Table 5 p. 35). The objective was to confirm the observations of pile 4A relative to performance and demonstate the scale up capability of the system. As indicated by the figure of blower demand (Fig. 105, VIII) temperature actuated ventilation occured at 20 hrs. into the run and full demand ventilation occured at 50 hrs. into the run. At 140 hrs. into the run the temperature control thermistor was switched to a thermistor located at a higher elevation of the pile. System controller malfunction occured at 140 hrs. At 160 hrs., the force ventilation rate was fixed at 100% "on" time without temperature control to investigate the effect of temperature on the rate of moisture loss.

Review of the rate of moisture loss during the run reveals the effect of temperature (see Fig. 128, VIII). During the initial 120 hrs. of the run the rate of moisture loss was similar to the rate observed by pile 4A of Run 4. Beyond 120 hrs. the rate of moisture loss was negative to 160 hrs. due to the ventilation system controller relay malfunction. Once full ventilation was restored, the rate of moisture loss increased, but, at a much lower rate than the initial 120 hrs. Additionally, pile temperature dropped precipitously beyond 160 hrs., as the rate of convective heat loss exceeded the rate of heat production.

The data, as plotted in Figure 128 VIII, reveals that the mechanically induced ventilation rate increase did not facilitate an increased rate of moisture loss by increasing the air flow. Secondly, it confirms that the rate of moisture loss is a function of ventilation rate and pile temperature. Lastly, it provides possible insight into the mechanism of moisture loss in the system.

The data confirms that microbial heat production and consequent pile temperature are necessary elements of pile moisture loss (drying), and that vaporization is the primary mechanism of water removal from the sludge. Watewater sludges are hydrophilic in nature (7). Effective drying of sludges can usually be obtained when heat is applied to the sludge. Heating of sludges produces a breakdown of the gel-like structure of the sludge (7). Collapse of the gel structure is attributed to the escape of water from the gel system due to its increased thermal activity (8).

Thus increased ventilation rates without subsequent increases in heat production results in excessive convective heat removal and subsequent attenuation of the rate of moisture loss of the pile.

H. The Rutgers USEPA-NJDEP-CCMUA Sewage Sludge Static Pile Composting Process

As predicted by the heat flow model and confirmed by the Data of Experimental Runs 1, 2, 3, 4 and 5, the Rutgers Static Pile Composting Process provides a maximal rate of heat production and consequent rate of moisture loss through control of pile temperature, facilitated by a mechanically induced, forced pressure ventilation pattern, that augments and is concurrent with the natural convective updraft of the pile. Ventilation of waste heat through evaporative cooling is the principle mechanism of convective heat loss, which is matched to the rate of microbial heat production at a pre set temperature of the pile.

The Rutgers Static Pile Composting Process, based on the principle of waste heat removal, provides a significant advantage over other composting processes: the ability to remove significant quantities of moisture from sludge through microbial activity. The consequence is the elimination of the requirement to burn fuel to dry sludge to similar moisture contents. The product of the process due to its low final moisture content and potential caloric value, warrents serious consideration for use in energy recovery process schemes for sewage sludge.

VII. FINAL CONSIDERATION

A treatment objective not previously considered in this report, as it is outside the scope of the experimentation, is disinfection of the waste. With respect to this objective a comparison between the waste heat retaining and the waste heat removing systems is inconclusive, as discussed in section A below.

Otherwise the waste heat removing system is conclusively superior on fundamental grounds, as already demonstrated, and also on grounds of convenience and flexibility of operation, as discussed in sections B through F below. Furthermore, this approach to composting lends itself to the formulation of well defined treatment objectives.

A. PATHOGEN DESTRUCTION

1. General

A characteristic of composting that destroys pathogenic organisms is the temperature elevation, and in composting this is the most thoroughly understood and easily evaluated mechanism of disinfection (44). Additionally, non-heat related mechanisms involving biological antagonisms are operative (45). Temperature and biological antagonisms are considered in the following, necessarily speculative, comparison of the two approaches to static pile composting with respect to pathogen kill.

Material near some of the edges of static piles, especially the "toes" near the ground, tends to be cool. This tendency is aggravated by vacuum-induced ventilation, which draws heat from the edges, whereas it is ameriorated by forced pressure ventilation, which transfers heat from the well-insulated interior to the edges. With vacuum, consequently, interior temperatures are very high and in this part of the pile pathogens are destroyed quickly. This benefit is partially offset, however, by the increase in the volume of cool edge material, where pathogens survive (6). Conversely, with forced pressure ventilation, in conjunction with the waste heat removing approach, the milder interior temperatures doubtless destroy pathogens more slowly. Less edge material, however, is entirely unexposed to disinfecting temperatures.

Non-heat related antagonisms inimical to pathogens accompany biological activity. Since activity is greater in piles managed according to the waste heat removing principle, these are presumably the site of greater disinfection through biological antagonisms.

Thus, neither approach to static pile composting is clearly superior with respect to disinfection.

Regardless, if regulatory authorities insist on a high temperature stage, this can be accomplished through modification of the waste heat removing process. For example, after a given period at temperatures favorable to organic matter decomposition a period of in-place high temperatures could be provided by moderating or shutting off the blower. The efficacy of this tactic was accidently demonstrated in run 3. Alternatively, after a period of time under temperature feedback control the material could be screened to remove woodchips, and the residue reformed elsewhere into curing piles. Such piles should be large to provide high temperatures and to minimize cool edge material.

2. Federal Criteria

"Interim Final Criteria" for the use of sewage sludge in agriculture were recently published in the Federal Register (46). According to these criteria, processing in such a manner as to "Significantly Reduce Pathogens" is sufficient if 1) there is no contact between the solid waste and the edible portion of the crop 2) public access is controlled for at least twelve months after the solid waste is applied 3) grazing by animals whose products are consumed by humans is prevented for a least one month. If, however, crops for direct human consumption are to be grown less than eighteen months after waste application, the processing must be in such a manner as to "Further Reduce Pathogens".

According to these criteria, static pile composting is considered to "Significantly Reduce Pathogens" when the minimum processing temperature is 40°C for 5 days, and during this period the temperature is greater than 55°C for 4 hours. Static pile composting is considered to "Further Reduce Pathogens" when the temperature is maintained at 55°C or greater for 3 days. We examine the temperature record of Run 4 in reference to these statements.

With respect to pile 4A, all of the positions recorded at least 40°C for 5 days. The second part of the requirement, that of exposure to 55°C for 4 hours, was met at all positions except for 4A1, where the temperature peaked at 53°C. Thus, with a minor exception, the criterion for significant pathogen reduction was met. The more **stringent** requirement is that of 55°C for 3 days. This was met at only 4 of the 11 positions (5, 11, 12, and 13). Thus the criterion for further pathogen reduction was not generally met in pile 4A.

In contrast, piles 4B and 4C, met the criterion for further pathogen reduction at all positions. This illustrates that the objectives of stabilization and drying conflicts with the objective of killing pathogens at the fastest possible rate (47). Nevertheless, as noted above (VIA1), the waste heat removing system can be managed to accomodate the need for a high temperature disinfection stage.

B. ADDITIONAL BENEFITS OF FORCED PRESSURE VENTILATION

1. Condensate

With vacuum induced ventilation, moisture in the exhaust stream condenses in the ductwork and in the condensate trap. As noted previously (IVD1), standing liquid in the ductwork can decrease air flow. The condensate is rich in nitrogen and sulfur compounds (48) and may be corrosive. Furthermore it is highly odorous. For these reasons condensate is a troublesome process sidestream.

A benefit of forced pressure ventilation is that the condensate problem is eliminated. This is because condensation occurs at the pile edges rather than in the ductwork. There is no liquid condensate to manage.

2. Freezing

Using vacuum-induced ventilation, the freezing of edge material was a problem in the Chicago area during winter operation (49). Forced pressure ventilation can be expected to ameliorate this type of problem.

C. PRODUCTION OF COMPOST

If potentially hazardous materials (e.g. heavy metals and nonbiodegradable industrial organic chemicals) are at acceptably low levels, a treatment objective can be to convert the waste to a finished compost for gardening and other sensitive uses. Generally accepted criteria of "degree of finish" are lacking. Nonetheless, the objective of drying the material as fast as possible, and that of producing a highly stabilized "garden grade" end product, are not compatible. Rather, to insure a high degree of stabilization the addition of water is necessary to prolong biological activity.

The addition should be scheduled to avoid any significant decrease in biological activity because of insufficient water. Perhaps a moisture content of 45% may be taken, provisionally, as the threshold to a water insufficiency. We found that the piles readily absored water applied by hose to the surface.

Alternatively, temperature feedback control might be used to decrease the moisture content only to the point of facilitating the removal of woodchips through screening. The partially processed material would then be reformed into curing piles, possibly with the addition of water. Curing requires little attention since the period of most intense oxygen demand is past. Nevertheless, it might be desirable to aid passive ventilation by forming the piles over perforated flexhose to promote convective updraft. Mechanically aided ventilation, however, should be restricted to the temperature feedback stage.

D. COMPOSTING OF ANAEROBICALLY DIGESTED VS RAW SLUDGE

These alternative microbial sludge treatment processes are compared in detail elsewhere (50). We note here that contemporary interest in composting, to a considerable extent, originates in regulatory pressures to find land-based means of ultimate disposal. The residue of this process, whether or not it is a "garden grade" compost, is aesthetically acceptable for land-based disposal. In contrast, anaerobically digested sludge is frequently unacceptable and for this reason it is sometimes composted. For example, two large sewage authorities plan to build new anaerobic digestion facilities with the intention of composting the digested sludge (8).

Unless there is evidence to the contrary, this "tandem" approach is questionable on grounds of economy. Although the production of methane is often noted as justification for anaerobic digestion, systematic economic analyses seem lacking. With respect to the production of a highly stabilized compost, prior digestion spares the composting process part of the burden. The amount of composting time saved, however, is probably trivial compared to the effort invested in the digestion. Furthermore, prior digestion decreases the amount of energy available to dry the sludge through composting by the waste heat removing system. Under ordinary circumstances prior digestion does not seem advantageous.

E. STARTING MOISTURE CONTENT

Mechanical dewatering (e.g. by filter belt press) is costly and should be minimized by starting the composting process with the highest practicable water content. The limiting moisture content is that which prevents the temperature ascent by decreasing porosity and oxygenation to the point of suppressing heat output. Once self-heating is underway, however, the material tends to dry and, provided that the waste contains sufficient energy, the terminal moisture content is independent of the starting content. Furthermore, starting with a lower water content than necessary shortens the period of decomposition. This is because unless water is added during processing it becomes the limiting factor.

Our experience is with raw sludge cake of approximately 75% moisture content, in conjunction with woodchips as the bulking agent. With this combination the temperature promptly increased after assembling the pile. We suspect that a somewhat wetter sludge cake would not have been troublesome.

F. DRYING

One way of viewing the new process is as the direct, in place, utilization of heat, generated microbially at the expense of putrescible organic matter, to dry the material. The use of the process for this purpose is represented by pile 4A, where the starting moisture content of 76% decreased to 22% in 15 days. Whether this extent of drying can be routinely achieved, or exceeded, can only be determined through experience. Reliable performance can be anticipated, however, because the mechanism of drying is well understood.

The elimination of woodchips from sludge composting is highly desirable. Efforts to replace woodchips with end-product compost have met with only limited success (51). The problem is one of moisture control, and therefore, the waste heat removing principle is a promising approach.

Drying solid waste renders it biologically inactive and relatively light in weight. Both characteristics are desirable with respect to storage and transport, in connection with resource recovery and ultimate disposal.

The usefulness of fuel derived from biomass is highly dependent on moisture content. In view of its capability to dry organic masses, the waste heat removing principle might find useful application in the preparation of fuel from agricultural and municipal waste.* The combinations of sewage sludge and municipal refuse (52), or leaves (53), are particularly attractive as starting materials. The refuse and leaves could serve as the bulking agent in place of woodchips or other costly material requiring post-composting separation.

The waste heat removing principle might find useful application in connection with the treatment of hazardous wastes. Microbial decomposition of industrial organic chemicals in composting, and the effect of process temperature on this objective, is the subject of separate reports (54, 55). In the present context, we note that it is essential to eliminate liquid effluents from facilities treating hazardous wastes. This objective could be pursued through vaporizing water with heat liberated biologically.

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* Screened 4A material yielded +4,750 Btu/lb, as received at the U.S Testing Co., Hoboken, N.J. This material had been stored for 1 year prior to this test, and its moisture content when tested was 45%.

VIII. REFERENCES AND NOTES

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21. Aside from the experiments which were consistent with the suggested design, summarized in Table 1, there are numerous expressions of opinion in the literature on composting regarding the relationship between temperature and biological activity. We comment on some of these.

An assertion that 80°C is desirable throughout the composting mass was not accompanied by data (Spohn, E. 1970. Compost Sci. 11:22). Furthermore the report is suspect because it was claimed, without benefit of supporting evidence, that "the microbial life is surprisingly abundant and diversified even at the temperature and a considerable number of fungi and actinomycetes could be identified." The temperature referred to is 80°C. Such findings would indeed be surprising, and in fact would revolutionize present day concepts of the temperature relationships of microbes! (See op cit 20.) We note Spohn's paper only because it was relied upon to suggest that extremely high temperatures are compatible with the objective of

rapid organic matter decomposition (Epstein, E. 1979. *In*, Workshop on the Health and Legal Implications of Sewage Sludge Composting, Vol. 2, Position Papers. Submitted to the Division of Problem-Focused Research Applications, National Science Foundation, by Energy Resources Co., Inc., Cambridge, Mass.).

Schulze's research established, among other things, the feasability of continuously thermophilic composting (Schulze, K. L. 1962. Appl. Microbiol. 10:108). It was not specifically designed to determine the temperature optimum, nor does it seem possible to do so with the published data. The problem is two-fold. First, the temperature fluctuated widely in both the batch and the continuously thermophilic trials. Secondly, with respect to the continuous trials, we found no way of resolving the effects of temperature and fresh substrate addition. Consequently, we do not agree with Schulze's interpretation that oxygen uptake and temperature were directly related throughout the range of 20°C to 70°C. Others have also questioned this interpretation (*op cit* 25).

Gray suggested 50°C - 60°C as the optimum (Gray, K. 1970. Compost Sci. 11(5):12) but his findings were based on oxygen uptake rates at different times in batch culture. Also, the temperature was artifically increased 5°C - 10°C every hour from 16°C - 70°C, allowing virtually no time for the microbial community to become adapted.

Using O_2 uptake as the criterion, Snell concluded that 45°C was optimal (Snell, J. R. 1960. Compost Sci. 1(2):28-30). He indicated, however, that this value might be too low because of uncontrolled moisture losses at higher temperatures.

Glathe felt that degradation was impaired at temperatures above 65°C (Glathe, H. 1959. *In*, Intern. Res. Group on Refuse Disposal, Bull. No. 7. U. S. Depth. HEW, PHS, CDC, Savannah, Ga.). Gotaas thought the optimum temperature was in the range of 50°C to 70°C, and probably around 60°C (Gotaas, H. B. 1956. WHO. Geneva). Golueke put the optimum lower, at 35° to 55°C (Golueke, C. G. 1972. Rodale Press, Inc. Emmaus, Pa). He suggested that efficiency decreased sharply above 55°C and became negligible above 70°C. Scott considered 45°C to 55°C to be optimal (Scott, J. 1961. Compost Sci. 2(3):7).

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28. Wiley's reports (op cit 22, 23; Wiley, J. S. 1955. Proc. Ind. Waste Conf. (Purdue Univ. No. 96, 10:306-313) are valuable but pose several interpretative problems.

In the last paper of the series Wiley stated that the experimental arrangement previously used for collecting water production data was faulty, and he described an improved arrangement. We used only the data which are identifiably valid (those given in op cit 23).

Wiley's conclusion that the highest temperatures attainable through self-heating are inimical to decomposition is supported by out statistical analysis of his published data. We used the instantaneous peak temperature throughout. Analysis of variance (ANOVA) for trials 36 and 40 (op cit 22) indicates that cooling composts so that a maximum temperature of 62° - 64°C was attained had a highly significant ($p<0.001$) beneficial effect on dry weight and volatile solids loss, and O_2 consumption, and perhaps a significant effect ($p<0.10$) on CO_2 production relative to the uncooled compost (71° - 73°C maximum temperatures). ANOVA for the data published in 1957 (op cit 23) indicates that composts which were cooled so that a maximum temperature of 56°, 60°, 62°, or 64°C was attained (the 62° and 64°C data are from op cit 22) and were also significantly better than uncolled composts which reached 69° - 73°C ($p<0.01$), and these were in turn better than those kept to 48°C ($p<0.01$). The values entered into the 69° - 73°C row of our Table 1 are means derived from all the uncooled controls.

Nevertheless, this conclusion might appear to be contradicted by three aspects of Wiley's papers.

i. He attempted to summarize all of the CO_2 and temperature observations in the form of a linear regression analysis, and similarly summarized the valid water production and temperature data. The resultant equations give the erroneous impression that CO_2 production and water production were positively correlated to temperature throughout the range of temperatures tested. The error was in the use of an inappropriate mathematical model.

ii. He noted that more water was removed from the material by composting at higher temperatures than at lower ones (e.g.

71^oC vs 56^oC).

We consider this observation to result from the use of a special heat exchanger, which detracts from evaporative cooling. In field practice the opposite relationship between temperature and drying holds, and the faster drying is at submaximal temperatures (see text).

iii. He noted that material composted at the intermediate temperatures, but not at the highest temperatures, tended to reheat (i.e., after the experiment's termination, and remoistening if necessary, the temperature increased). Reheating was considered a sign of poor product quality, the implication being that greater reheating would occur if readily available organic material remained. Our view is that, except for carefully controlled conditions, reheating is virtually meaningless as a test. We note two reasons for this conclusion: the material that peaked at the higher temperatures may have failed to reheat because the population was debilitated; large piles of organic materials are prone to self-heat, even though they consist of relatively stable organic matter (e.g., virgin woodchips, peat moss).

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33. A fundamentally different approach to temperature control is to limit heat output through deliberate O_2 starvation. (Schulze, K. L. United States Patent No. 3,138,448, issued 23 June 1964. From, Solid Waste Information Retrieval System, accession No. 5893). This is in conflict, however, with the goal of maximizing organic matter decomposition. Regardless, the approach was abanded in the full scale operation (op cit 42).

34. Wiley and Pearce judged the effect of three ventilation rates in terms of the rate of temperature ascent (Wiley, J. S. and G. W. Pearce, 1957). Trans. Amer. Soc. Civil Eng. 122:1009. We do not consider this a suitable criterion because the interaction between heat output and temperature is an overriding factor.

Galler and Davey reported that the rate of oxygen uptake was greater in well ventilated composting material compared to poorly ventilated material (Galler, W. W. and C. B. Davey. 1971. Amer. Soc. Agr. Eng. Proc. p159). The cumulative uptake, however, was similar for the two ventilation levels.

Other studies, typified by Schulze's (op cit 21), provide data showing the change in oxygen residual over time for a given air flow rate. This data is not useful for the present purpose since the change in oxygen residual is both a determinant and an effect of biological activity.

35. For reasons outlined elsewhere (op cit 18) water activity (a_w) provides a superior measurement of the water status in relation to microbial requirements. Such data are lacking in the literature on composting.

The conclusion that a water content of 50 to 60% is generally favorable for composting process performance is based on experimentation in which an attempt was made to isolate the effect of moisture from other variables (loc.cit 26; Anon. 1955. Civil Sanit. Eng. Dept., Mich. State Univ., Ann Arbor; Schulze, K. L. Compost Sci. 2(2):32), and also on general observations (Stoller, B. B., F. B. Smith, and P. E. Brown. 1937. J. Amer. Soc. Agron. 29:717; Poincelot, R. P. 1972. Conn. Agr. Exp. Sta. New Haven, Bull. 727).

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37. Analysis of Variance (ANOVA) for summed values of CO_2 and O_2. The null hypothesis (Ho) is that the mean values for the sum of $CO_2 + O_2$ in all 3 trials are the same ($\mu_1 = \mu_2 = \mu_3$).

The alternative hypothesis (Ha) is that the mean value for the 3 trials are different.

ANOVA TABLE

Sources of variation	Degrees of freedom	Sum of squares	Mean square	F. ratio
Trials	2	.529	.2645	.2534
Random	60	62.641	1.0440	
Total	62	63.17		

Critical value of F .01(2,60) = 5.79 .2534< 5.79

Therefore, we accept the null hypothesis and assume that the means are equal.

38. The volume of air moved by a blower is independent of temperature,

whereas the mass of air moved is dependent on temperature. This is because a given volume of cool air has more mass (is denser) than the same volume of warm air.

In the vacuum mode the blower moves air which has passed through the pile and is hot and of low density. The density is estimated to be 0.0563 lb/ft^3, assuming an air temperature of 68°C and 100% relative humidity. In the pressure mode the blower moves cool, relatively dense, air into the pile. The density is estimated to be 0.0645 lb/ft^3, assuming an air temperature of 21°C and 60% relative humidity. This density difference results in the forced pressure mode being 15% more efficient in terms of utilizing the installed blower capacity.

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41. Sample calculation for transient heat output based on Pile 4A at hr 100

Initial Data

Tambient = 14.9°C

Duration = 120 min/120 min + 120 min/120 min (over 4 hour interval)

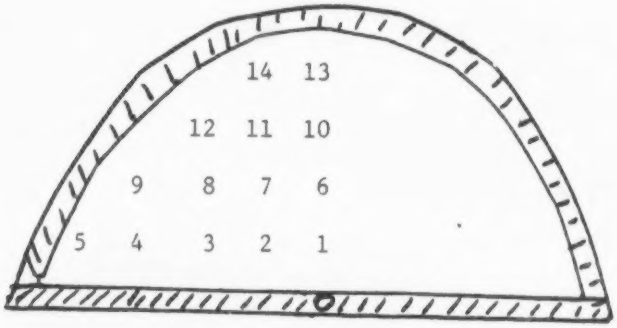
$T_1 = 48.0^\circ C$ $T_2 = 54.5^\circ C$ $T_3 = 37.4^\circ C$ $T_4 = 46.2^\circ C$

$T_5 = 48.3^\circ C$ $T_6 = 57.1^\circ C$ $T_7 = 55.0^\circ C$ $T_8 = 55.3^\circ C$

$T_9 = 48.3^\circ C$ T_{10}= No data $T_{11} = 57.2^\circ C$ $T_{12} = 64.2^\circ C$

$T_{13} = 60.3^\circ C$ T_{14}= No data

Location Key



Q total = $Q_{cond.} + Q\Delta T + Q_{conv.}$

Q Conduction = $\frac{lc}{L}$ $(\overline{T}$ - T surroundings)

lc= Thermal conductivity (Btu/ft hr °F) of the woodchip base and cover approximated at 0.05 Btu/ft hr °F

A = Area of surface exposed to surroundings

Approximated to be a come

$h = 7' \quad r = 7'$

$A = S_{top} + S_{base}$

$A = ¶(7) \quad 2\ (7)^2 \quad + ¶49$

$A = 217.7 + 153.9$

$A = 371.6\ ft^2$

L = woodchip (insulating material thickness)

thickness = 0.5 ft

$\overline{T}$ = Average pile temperature approximated to be

$$\frac{T_1 + T_2 + \ldots T_n}{n}$$

= 53.3°C

T surroundings = weighted average of ground = 60°F temperature and average ambient temperature = 72°F

Corresponding to proportion of affected area (0.4:0.6)

= 0.4(60°F) + 0.6 (72°F)

= 67°F

$Q_{cond} = \frac{(0.05)\ (371.6)}{(0.5)} \quad (\overline{T}^{o}C\ (9/5) + 32)^{o}F - 67^{o}F)$

$Q_{cond} = 66.89\ (\overline{T}^{o}C - 19.4)$

$Q_{cond} = 66.89\ (55.3 - 19.4) = 2265$ Btu/hr

$Q\Delta\overline{T} = MC\Delta\overline{T}$

M = sludge woodchip mass = 14,000

C = specific heat of mass approximated to be that of

water = 1.0 $\frac{\text{Btu}}{\text{lb}^{\circ}\text{F}}$

$$\Delta\overline{T} = \frac{(\overline{T}_{100} - \overline{T}_{96})^{\circ}\text{C}}{4 \text{ hr}}$$

$\overline{T}_{100} = 53.3^{\circ}\text{C}$

$\overline{T}_{96} = 50.7^{\circ}\text{C}$

$\Delta\overline{T} = 0.650^{\circ}\text{C/hr} = 1.17^{\circ}\text{F/hr}$

$Q\Delta\overline{T} = (14{,}000)\ (1.0)\ (1.17)\ \text{Btu/hr} = 16{,}380\ \frac{\text{Btu}}{\text{hr}}$

$Q_{conv} = m\ (h_{out} - h_{in})$

$m = V \frac{\text{ft}^3}{\text{hr}} \times \frac{1 \text{ lb}}{\nu \text{ft}^3} \times \text{duration } (\%)$

$V = 530 \frac{\text{ft}^3}{\text{min}}$ (Dayton data)

$X \frac{60 \text{ min}}{\text{hr}} = 31{,}800 \frac{\text{ft}^3}{\text{hr}}$

ν = from psychrometric chart for $t_{amb} = 14.9^{\circ}\text{C}$

$= 13.2 \frac{\text{ft}^3}{\text{lbm}}$ R. H. = assumed 60%

Duration = $\frac{120 + 120}{240 \text{ min}}$ min = 100% = 1.00

$m = 31{,}800\ (1/13.2)\ (1.00) = 2409 \frac{\text{lbm}}{\text{hr}}$

h_{out} from psychrometric chart

R. H. = 100% (assumed)

$T = \overline{T}_{out}$ which is weighted average of probes near surface

$\overline{T}_{out} = 0.1(T_5) + 0.2\ (T_9) + 0.3\ (T_{12}) + 0.4\ (T_{13})$

$\overline{T}_{out} = 59.8^{\circ}\text{C}$

h_{out} = 186 Btu/lb air

h_{in} from psychrometric chart for ambient conditions (T = 14.9°C R. H. = 60%)

$$h_{in} = 21 \text{ Btu/lb}_{air}$$

$$Q_{conv} = 2409\ (186-21)\ \frac{\text{Btu}}{\text{hr}} = 397{,}500\ \frac{\text{Btu}}{\text{hr}}$$

$$Q \text{ total} = Q_{cond} + Q\Delta T + Q_{conv}$$

$$= 2265 + 16{,}380 + 397{,}500 \pm 416{,}145\ \frac{\text{Btu}}{\text{hr}}$$

Values for Enthalpy, the relative heat content of the air, were obtained in three separate forms.

1) ASHRAE Psychrometric Chart No. 1 (for ambient conditions at seal level)

2) ASHRAE Psychrometric Chart No. 3 (for high temperatures of 120°F and 100% R. H. at sea level).

3) The equation

$$h = \omega h_v + C_{po}\ (\text{air})\ T \text{ and } \omega = (\text{R.H.})\ (0.622)\ \frac{Pv}{Patm - Pv}\ \frac{\text{lb vapor}}{\text{lb dry air}}$$

$$C_{po}\ (\text{air}) = 0.240\ \frac{\text{Btu}}{\text{lb }^{\circ}\text{F}}$$

T = air temperature (°F)

R.H. = relative humidity

Patm = atmospheric pressure = 14.698 psi

P_v = vapor pressure (steam tables)

h_v = enthalpy of water vapor (steam tables)

ν (nu): volumetric density (ft/lb)

π (pi): constant = 3.14 (no units)

p (rho): mass density (lb/ft^3)

σ (sigma) Stephan - Boltzman Constant (0.1713×10^{-8} Btu/hr ft°R)

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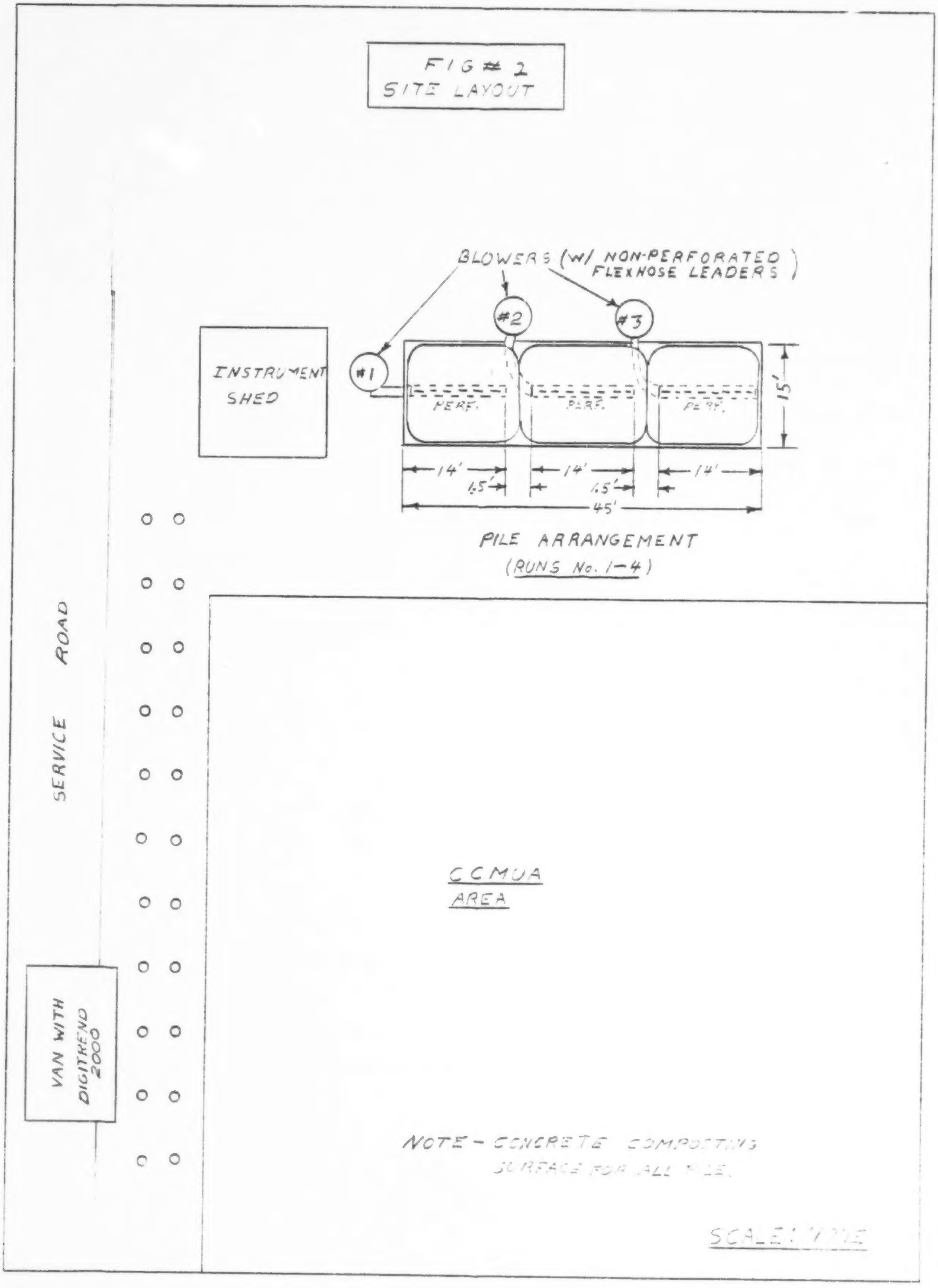
FIG # 2
SITE LAYOUT

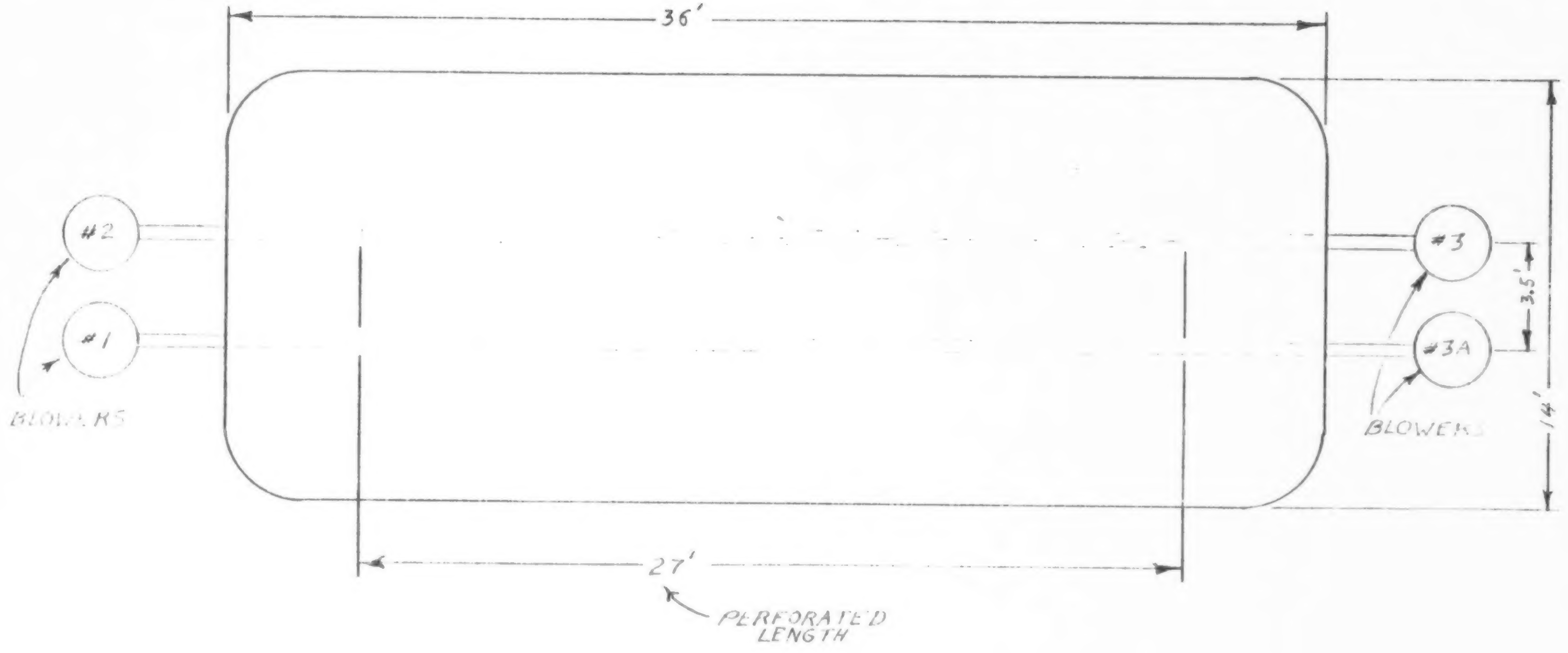

BLOWERS (W/ NON-PERFORATED FLEXHOSE LEADERS)
#1
#2
#3
INSTRUMENT SHED
PERF.
PERF.
PERF.
15'
14'
14'
14'
1.5'
1.5'
45'
SERVICE ROAD
VAN WITH DIGITREND 2000
CCMUA AREA

PILE ARRANGEMENT
(RUNS No. 1-4)

NOTE - CONCRETE COMPOSTING
SURFACE FOR ALL PILE.

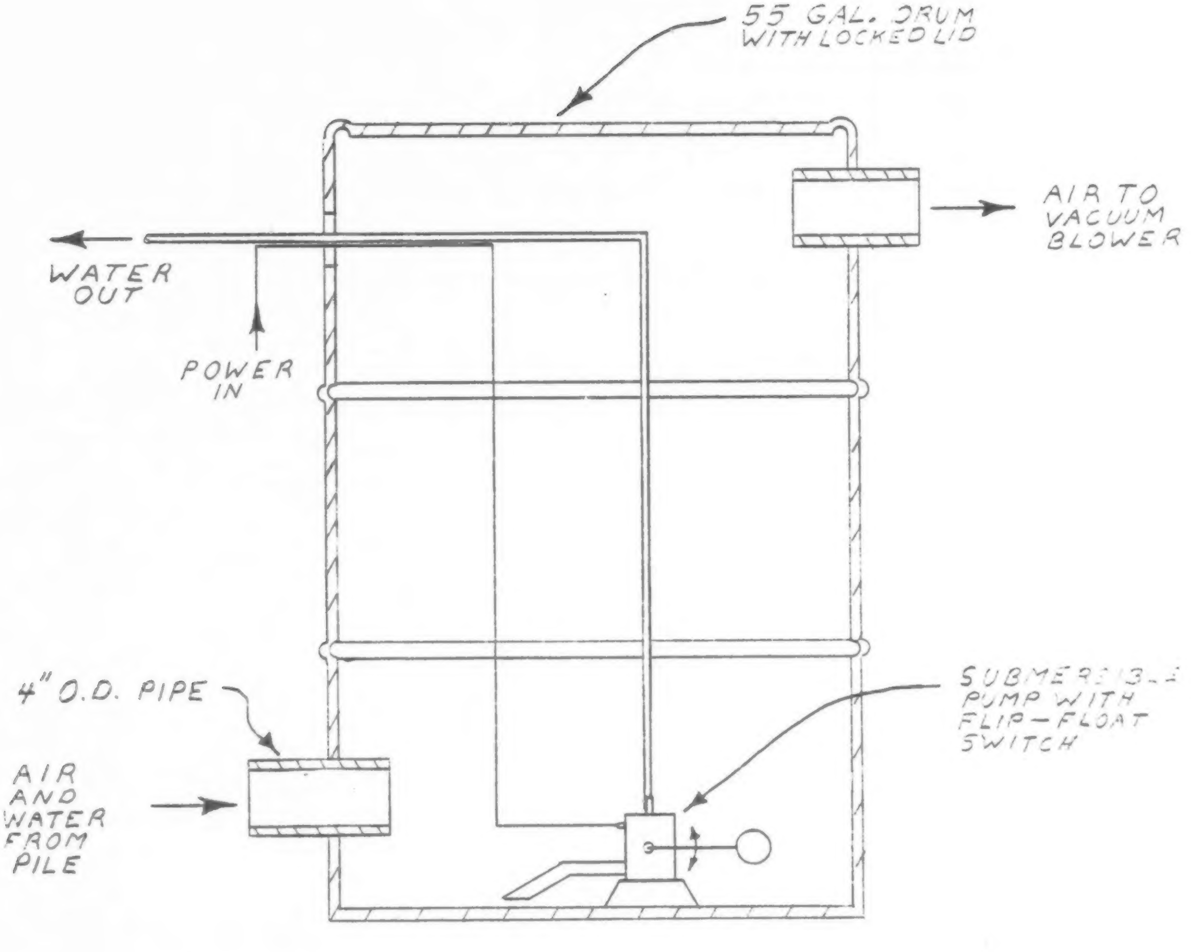
SCALE: NONE

FIG # 3
PILE LAYOUT
FOR RUN No. 5


36'
#2
#1
BLOWERS
#3
#3A
BLOWERS
3.5'
14'
27'
PERFORATED LENGTH

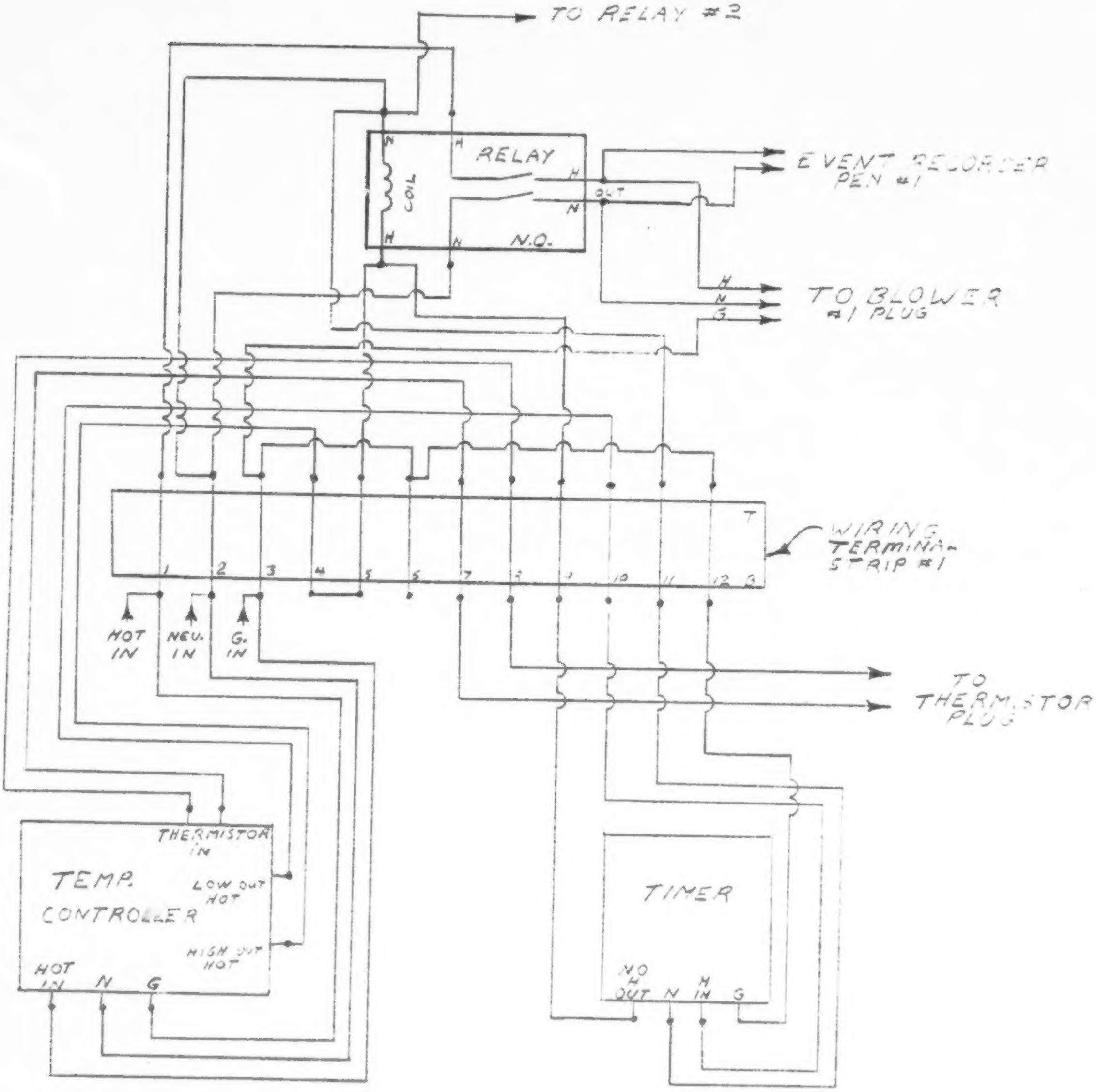
SCALE: 3/16" = 1.0'

FIG # 4
WATER TRAP FOR
VACUUM INDUCED
VENTILATION SYSTEM


55 GAL. DRUM
WITH LOCKED LID
AIR TO
VACUUM
BLOWER
WATER
OUT
POWER
IN
4" O.D. PIPE
SUBMERSIBLE
PUMP WITH
FLIP-FLOAT
SWITCH
AIR
AND
WATER
FROM
PILE

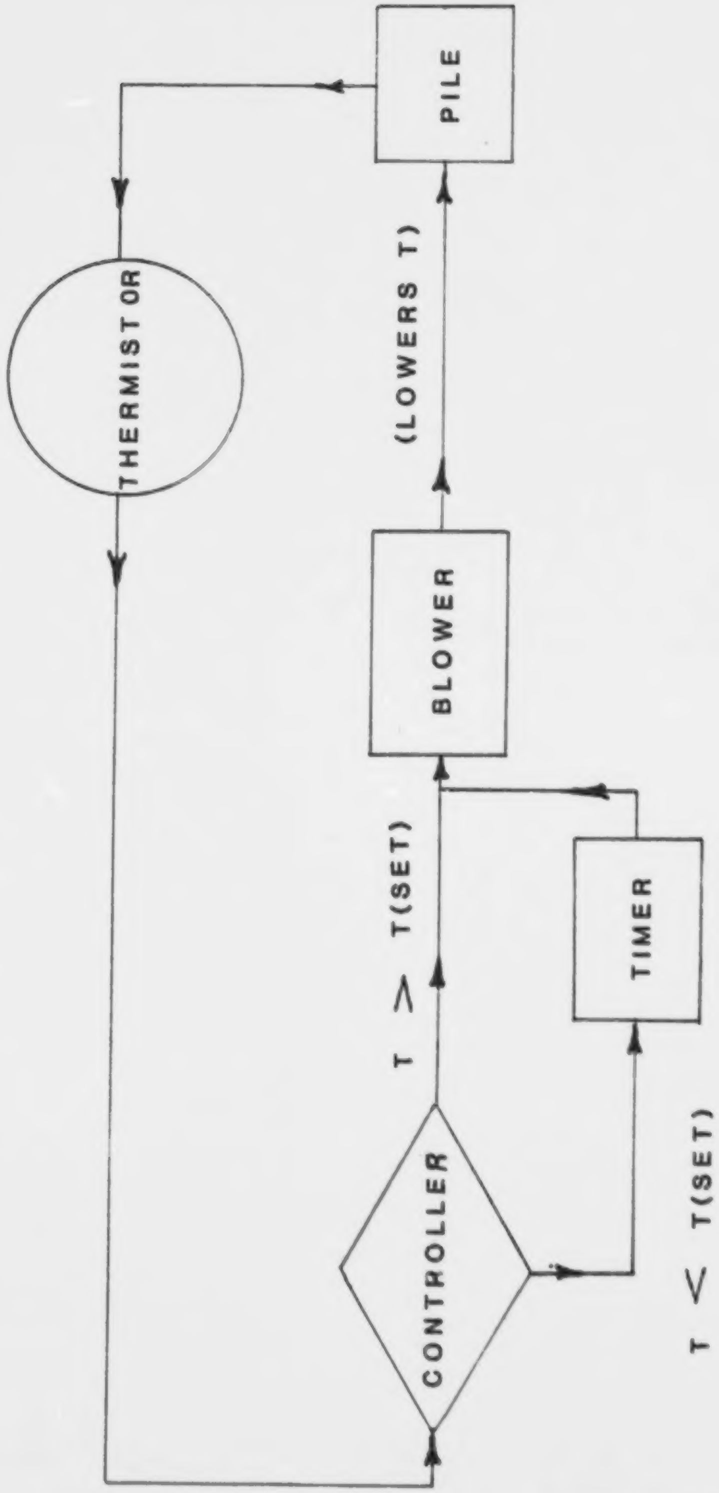
SCALE: NONE

FIG # 5
No. 1 BLOWER, TEMPERATURE
ACTUATED CONTROL SYSTEM
WIRING DIAGRAM


TO RELAY #2
RELAY
COIL
N
H
H
N
H
N
OUT
N.O.
EVENT RECORDER
PEN #1
H
N
G
TO BLOWER
#1 PLUG
T
WIRING
TERMINAL
STRIP #1
1
2
3
4
5
6
7
8
9
10
11
12
G
HOT
IN
NEU.
IN
G.
IN
TO
THERMISTOR
PLUG
THERMISTOR
IN
TEMP.
CONTROLLER
LOW OUT
HOT
HIGH OUT
HOT
HOT
IN
N
G
TIMER
NO
H
OUT
N
H
IN
G

NOTE: No. 2 AND No. 3 SYSTEMS
ARE IDENTICAL

FIGURE 6


THERMISTOR
PILE
(LOWERS T)
BLOWER
T > T(SET)
TIMER
CONTROLLER
T < T(SET)

BLOWER CONTROL
FLOW DIAGRAM
(RUNS 3 THRU 5)

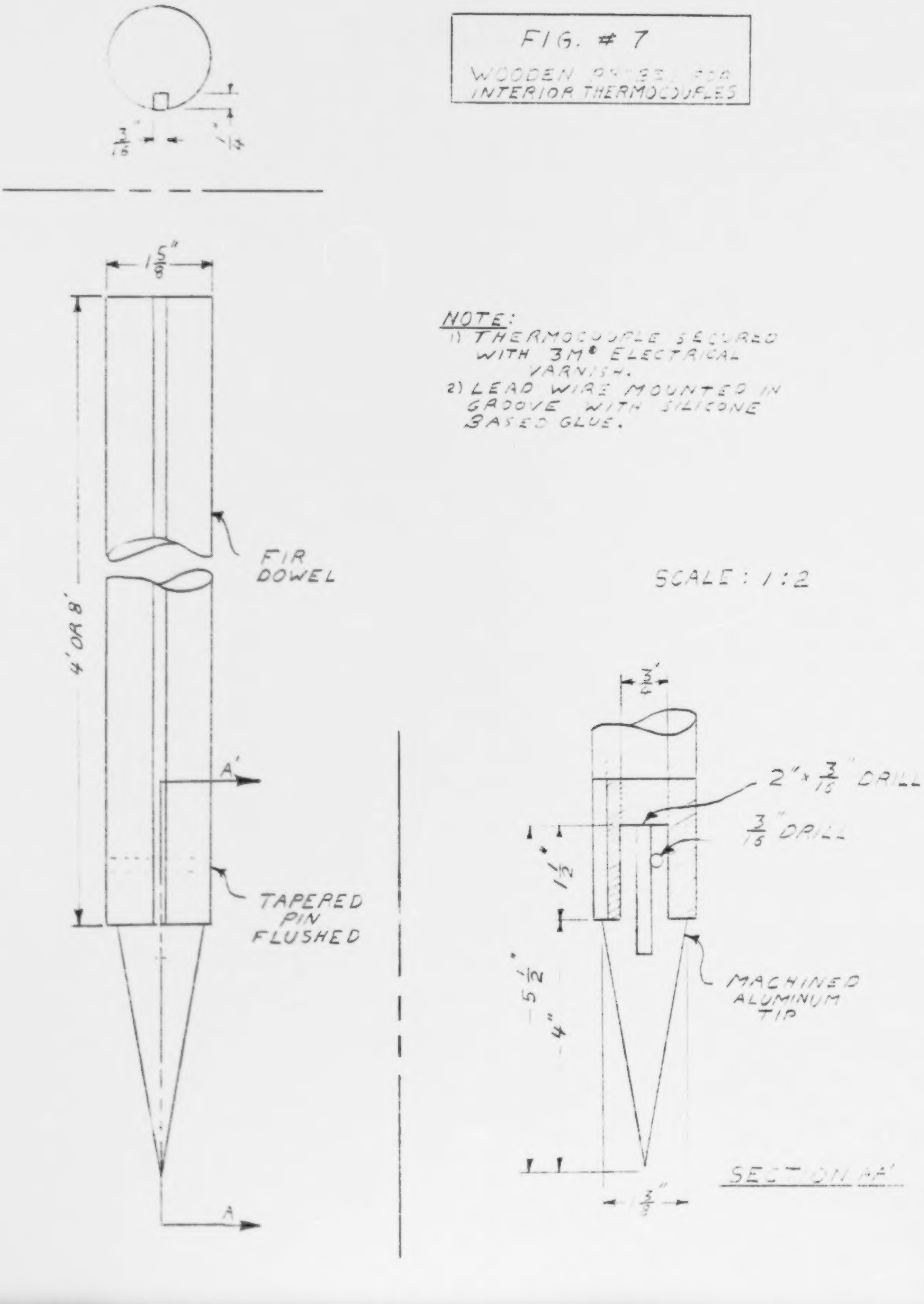

3/16"
1 5/8"
4' OR 8'
FIR DOWEL
TAPERED PIN FLUSHED
A'
A
3/4'
2" × 3/16" DRILL
3/16" DRILL
1 1/2"
5 1/2"
4"
MACHINED ALUMINUM TIP
1 3/8"
SECTION AA'

FIG. # 7

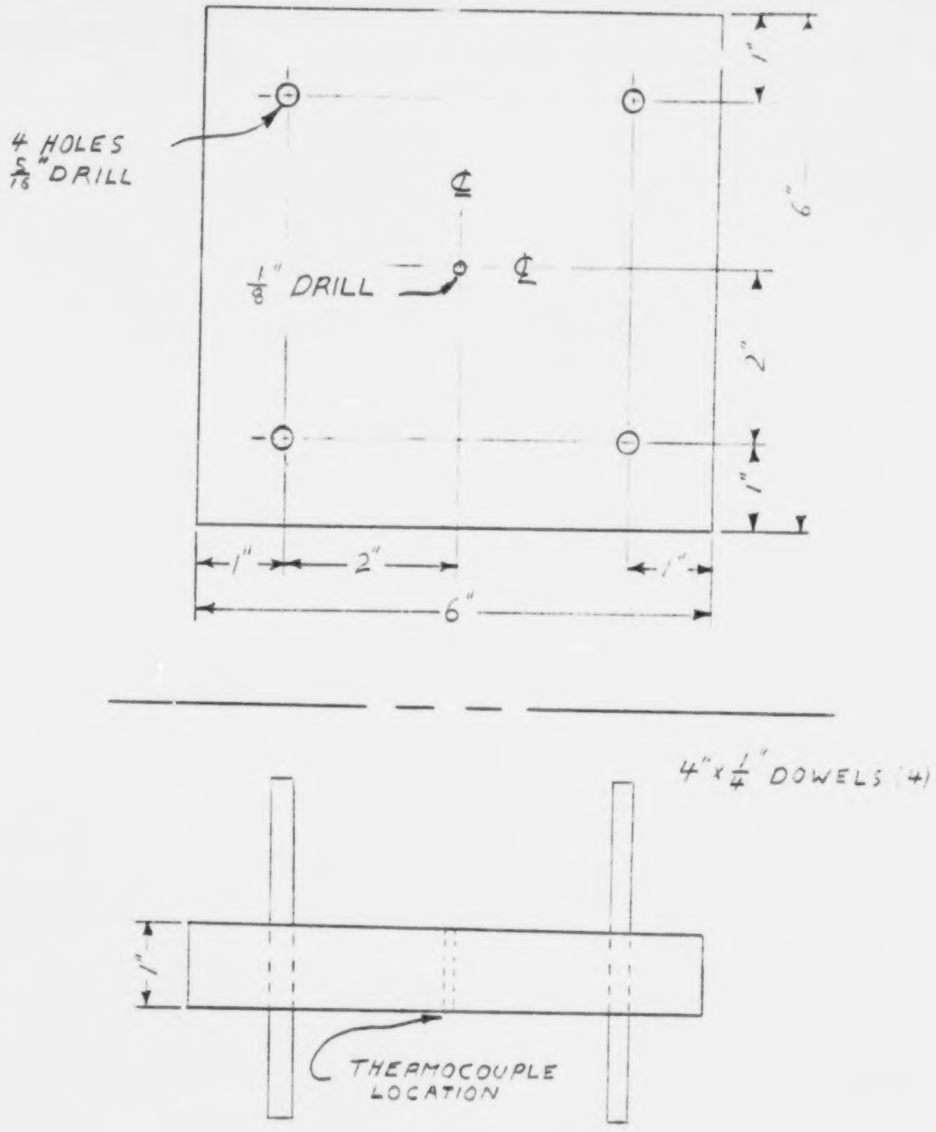
WOODEN PROBES FOR INTERIOR THERMOCOUPLES

NOTE:
1) THERMOCOUPLE SECURED WITH 3M® ELECTRICAL VARNISH.
2) LEAD WIRE MOUNTED IN GROOVE WITH SILICONE BASED GLUE.

SCALE: 1:2

FIG. # 8

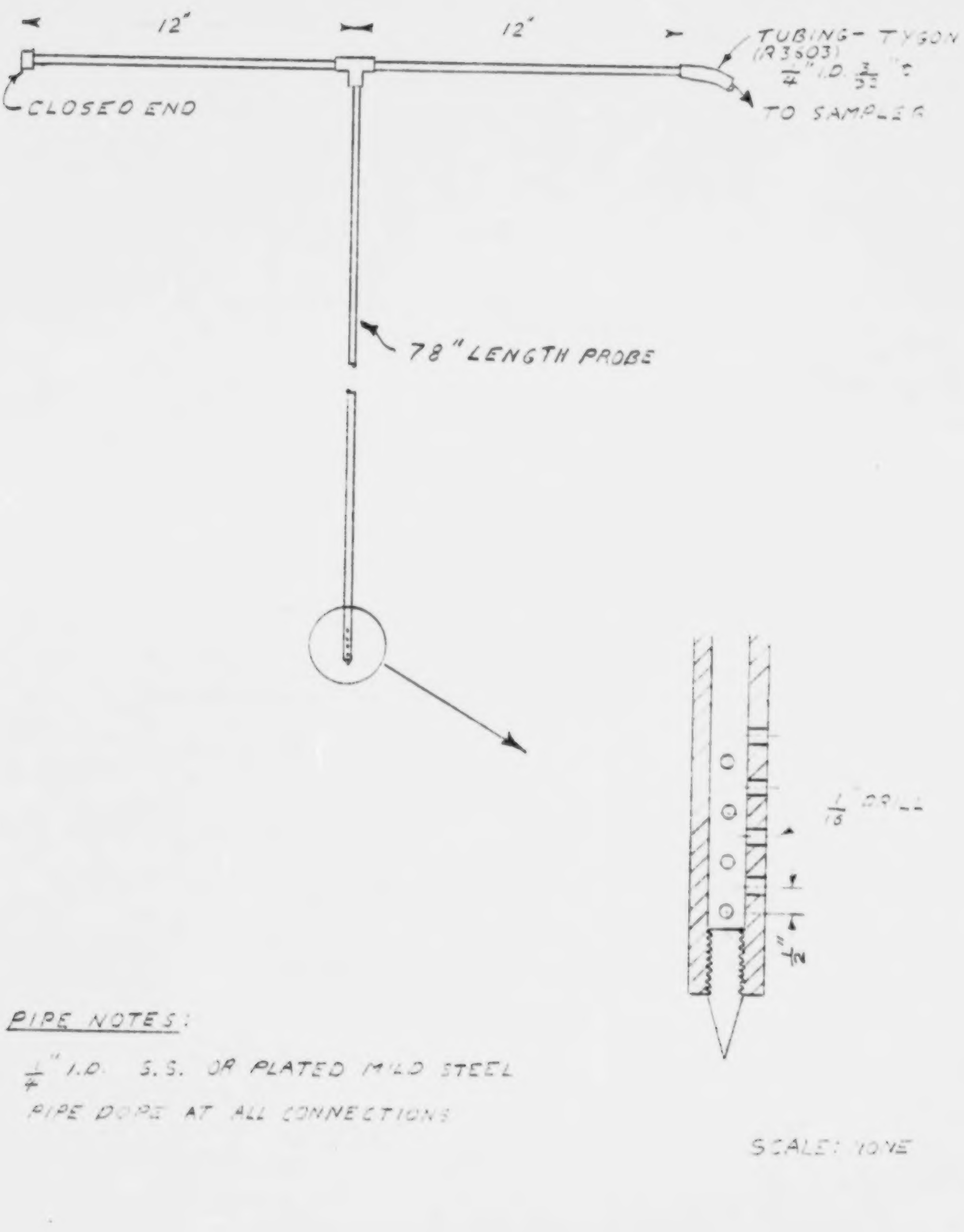
SURFACE MOUNTS FOR EXTERIOR THERMOCOUPLES


4 HOLES
$\frac{5}{16}$" DRILL
℄
$\frac{1}{8}$" DRILL
℄
1"
6"
2"
1"
1"
2"
1"
6"
4" x $\frac{1}{4}$" DOWELS (4)
1"
THERMOCOUPLE LOCATION

SCALE: NONE

MATERIAL: 5" x 1" CLEAR PINE STOCK

FIG. # 9
PILE GAS SAMPLING PROBES


12"
12"
CLOSED END
TUBING- TYGON[3] (R3603) $\frac{1}{4}$" I.D. $\frac{3}{32}$" T
TO SAMPLER
78" LENGTH PROBE
$\frac{1}{16}$" DRILL
$\frac{1}{2}$"

PIPE NOTES:

$\frac{1}{4}$" I.D. S.S. OR PLATED MILD STEEL
PIPE DOPE AT ALL CONNECTIONS

SCALE: NONE

FIG #10
SAMPLE SYSTEM-
CYCLE ACTUATION
DEVICE

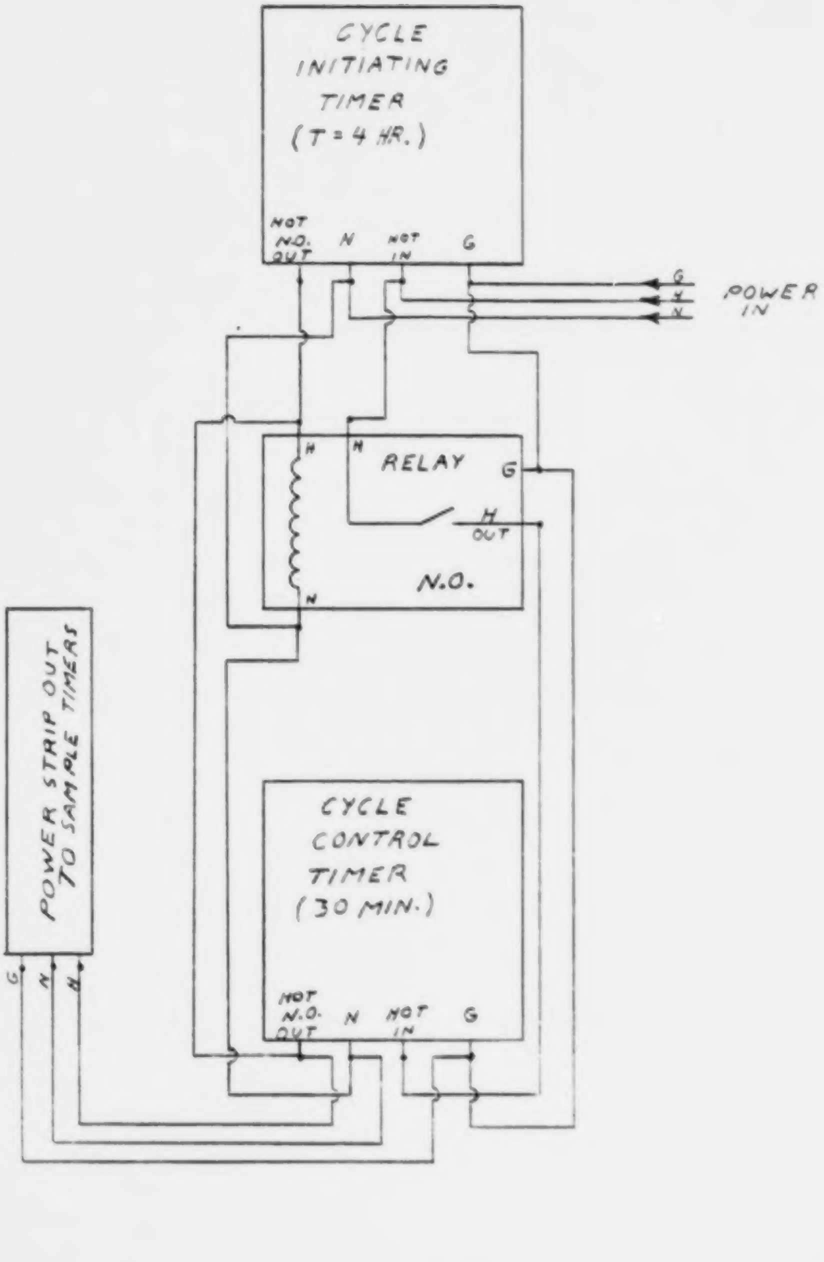
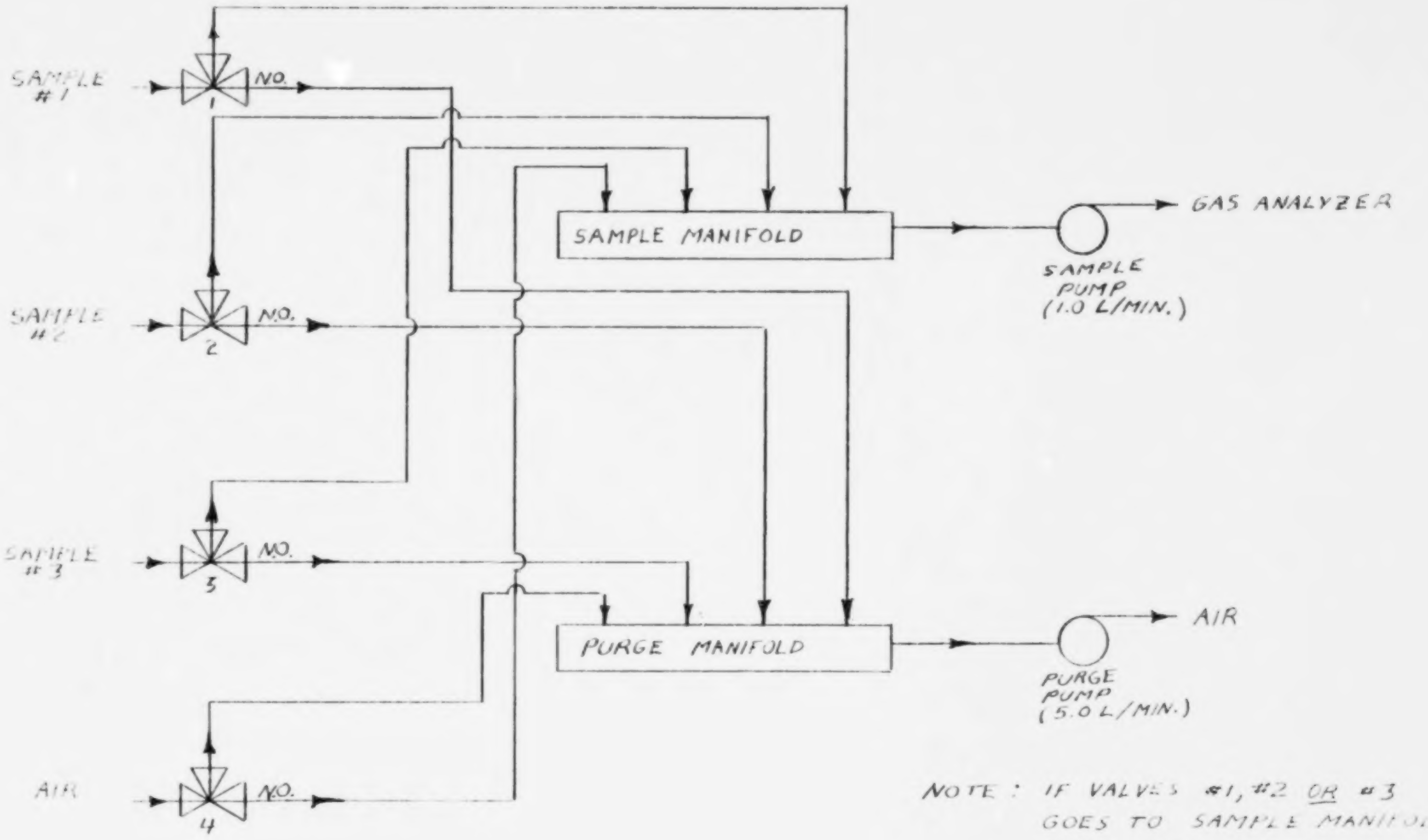

CYCLE
INITIATING
TIMER
(T=4 HR.)
HOT N.O. OUT
N
HOT IN
G
G
H
N
POWER IN
H
H
RELAY
G
H OUT
N
N.O.
POWER STRIP OUT TO SAMPLE TIMERS
G
N
H
CYCLE
CONTROL
TIMER
(30 MIN.)
HOT N.O. OUT
N
HOT IN
G

FIG # 11
GAS MULTIPLEXING
SYSTEM—PNEUMATIC


SAMPLE #1
SAMPLE #2
SAMPLE #3
AIR
NO.
1
2
3
4
SAMPLE MANIFOLD
PURGE MANIFOLD
SAMPLE PUMP (1.0 L/MIN.)
PURGE PUMP (5.0 L/MIN.)
GAS ANALYZER
AIR

NOTE : IF VALVES #1, #2 OR #3 GOES TO SAMPLE MANIFOLD, THEN VALVE #4 GOES TO PURGE.

FIG # 12
GAS MULTIPLEXING
SYSTEM—ELECTRICAL

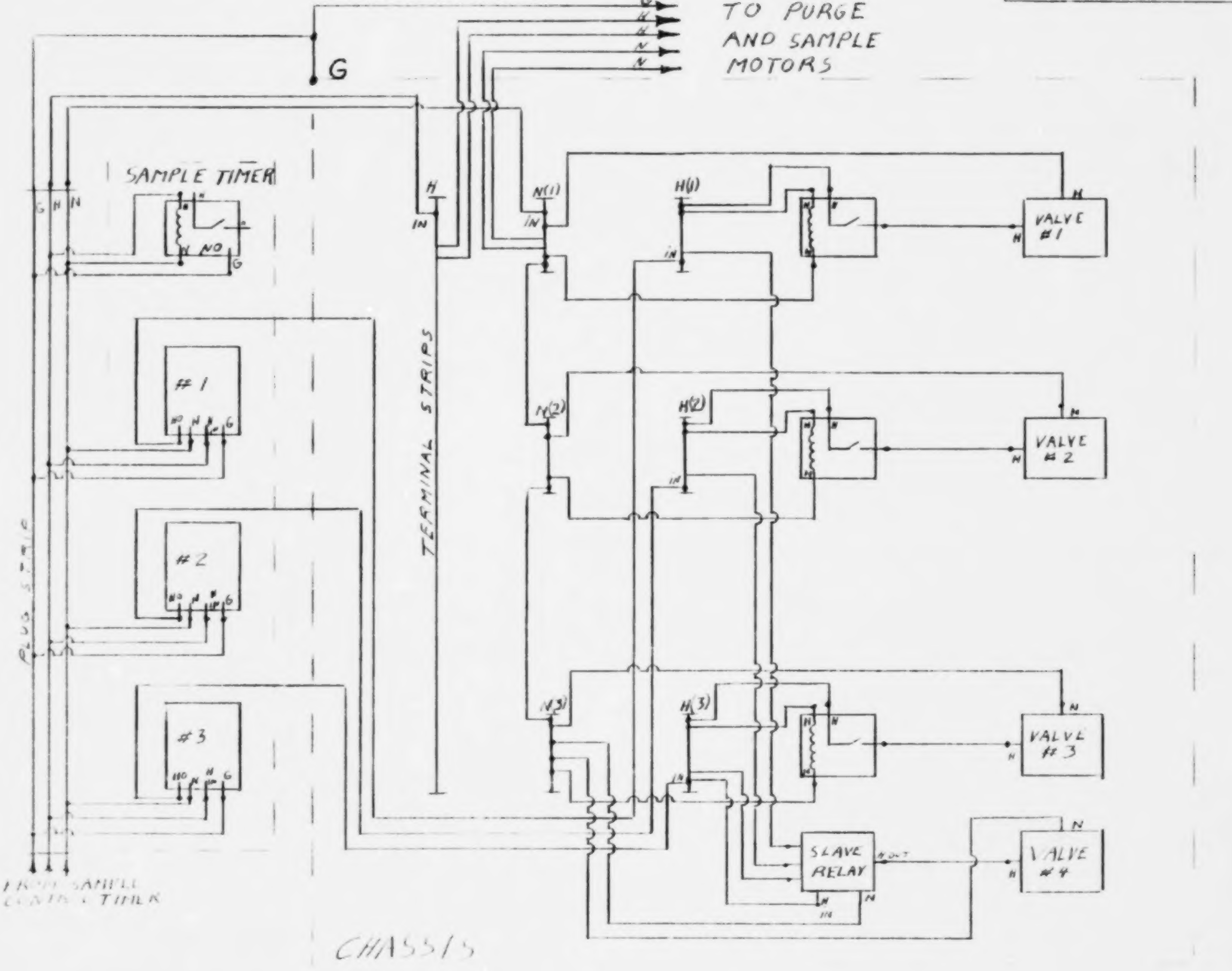
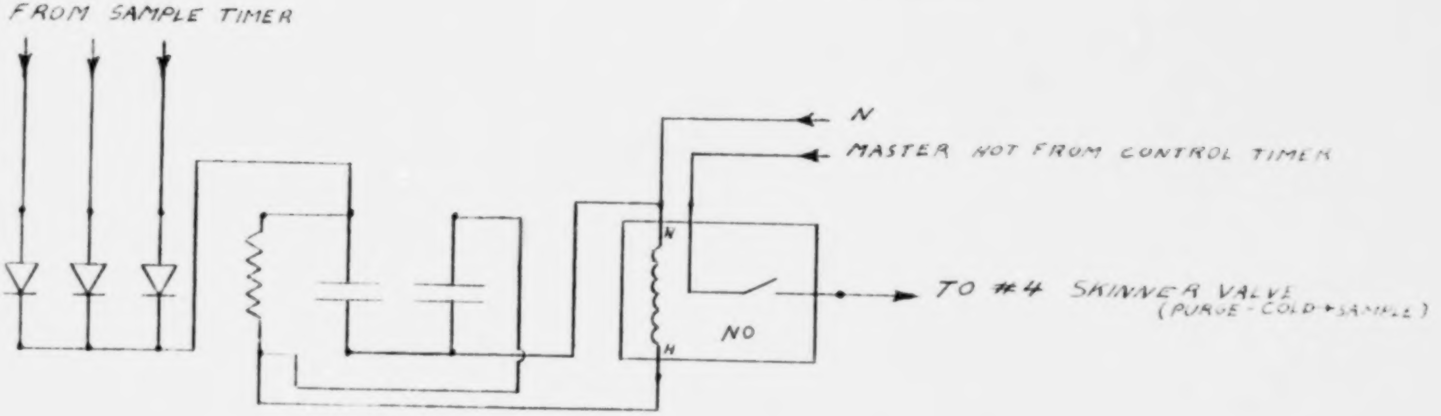

TO PURGE AND SAMPLE MOTORS
G
H
H
N
N
G
SAMPLE TIMER
G H N
NO
TERMINAL STRIPS
H
IN
N(1)
IN
H(1)
IN
N(2)
H(2)
IN
N(3)
H(3)
IN
VALVE #1
VALVE #2
VALVE #3
VALVE #4
SLAVE RELAY
N OUT
#1
#2
#3
NO
N
G
PLUG STRIP
FROM SAMPLE CONTROL TIMER
CHASSIS

FIG # 12A
PURGE VALVE
SLAVE RELAY


FROM SAMPLE TIMER
N
MASTER HOT FROM CONTROL TIMER
N
H
NO
TO #4 SKINNER VALVE
(PURGE - COLD + SAMPLE)

PARTS LIST

1) DIODES (3) — WER 170
2) RESISTOR — 1K 10% (7613 IRC PWIC)
3) CAPACITOR — SPRAGUE TE-1509
20-150DC USA 7317H
4) RELAY — POTTER + BRUNFIELD
KA501 110VDC

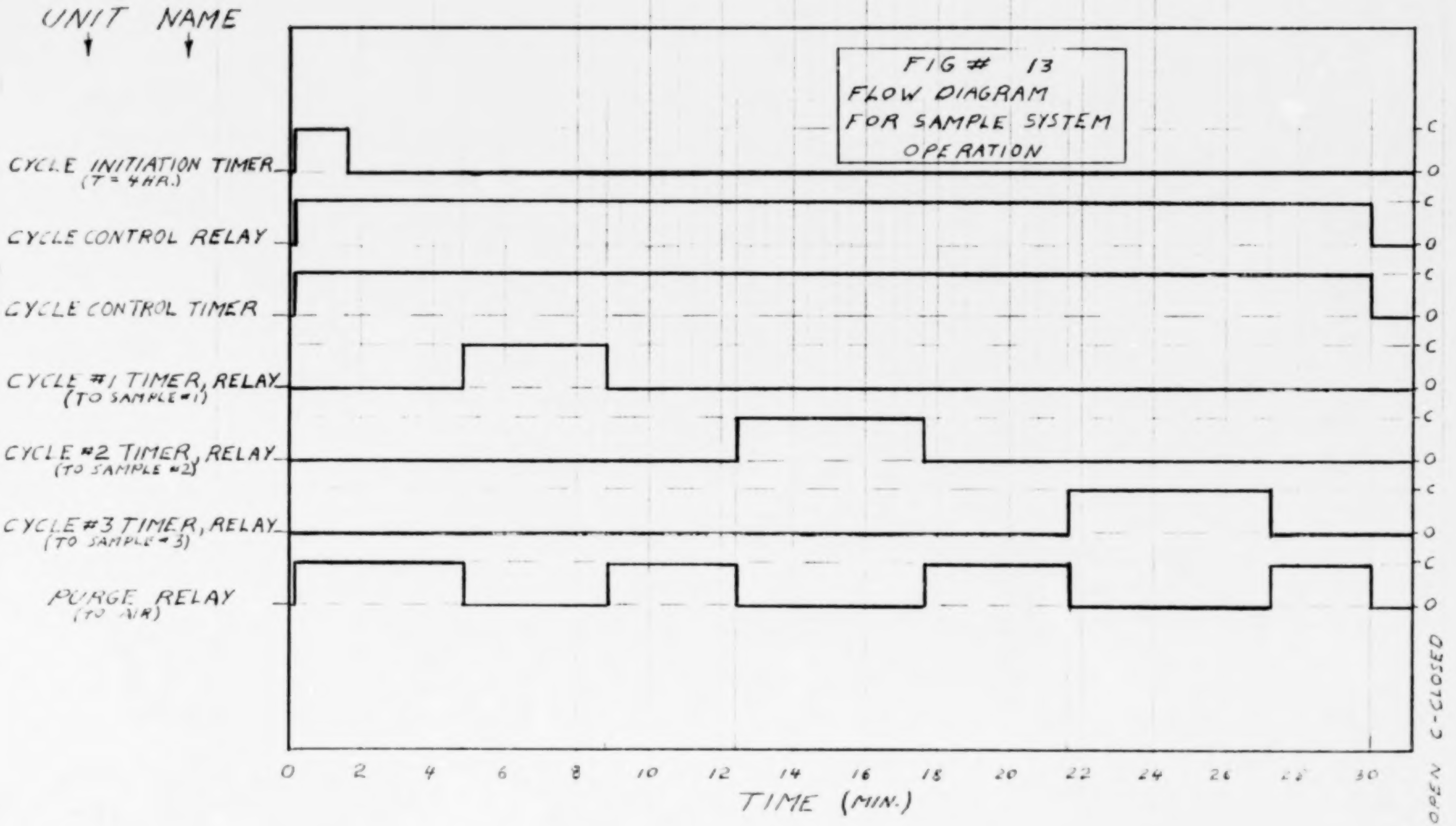


FIG # 13
FLOW DIAGRAM
FOR SAMPLE SYSTEM
OPERATION

CO_2 VS O_2

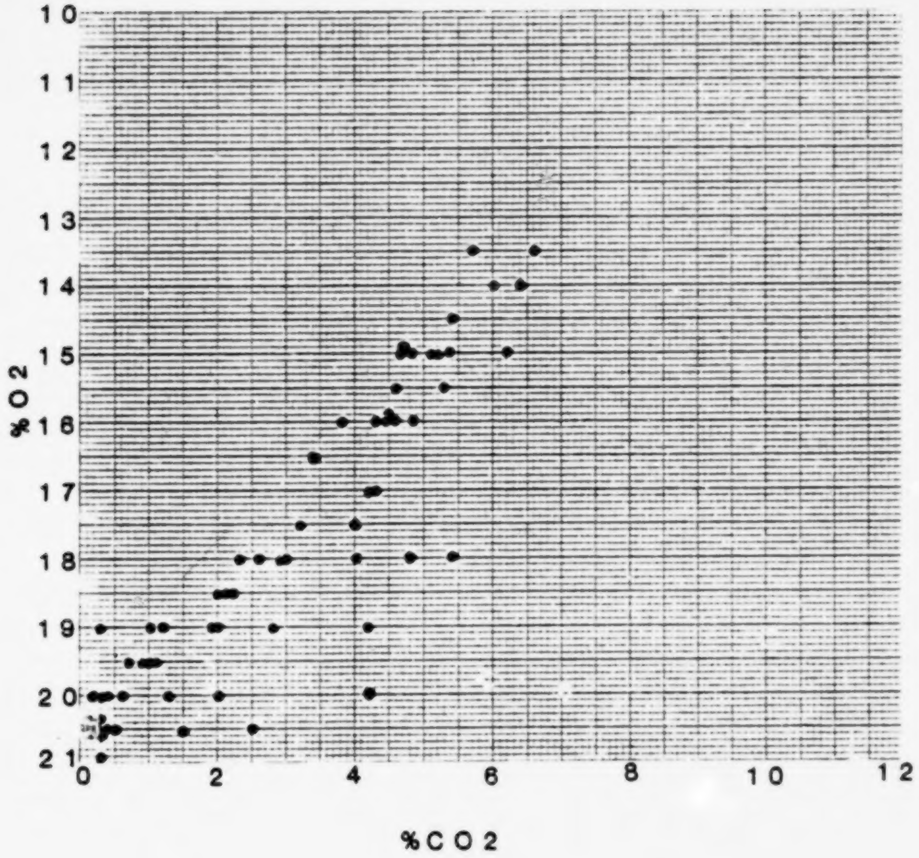
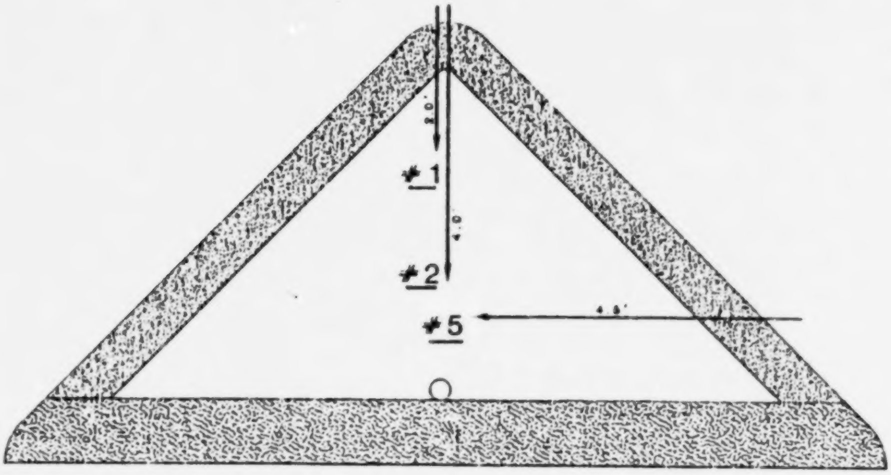


FIG 14

RUN #1, #2, #3
INTERIOR (I) PROBE LOCATION KEY

Center Cross Section



Longitudinal Cross Section

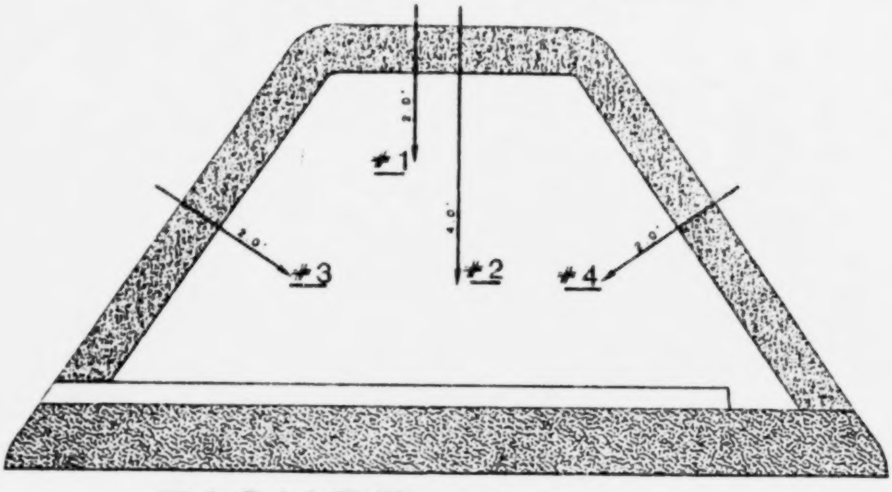

2.0'
#1
4.0'
2.0'
#3
#2
#4
2.0'

FIGURE 15

TEMP. VS TIME:
PILE 1A, PROBE #1,3

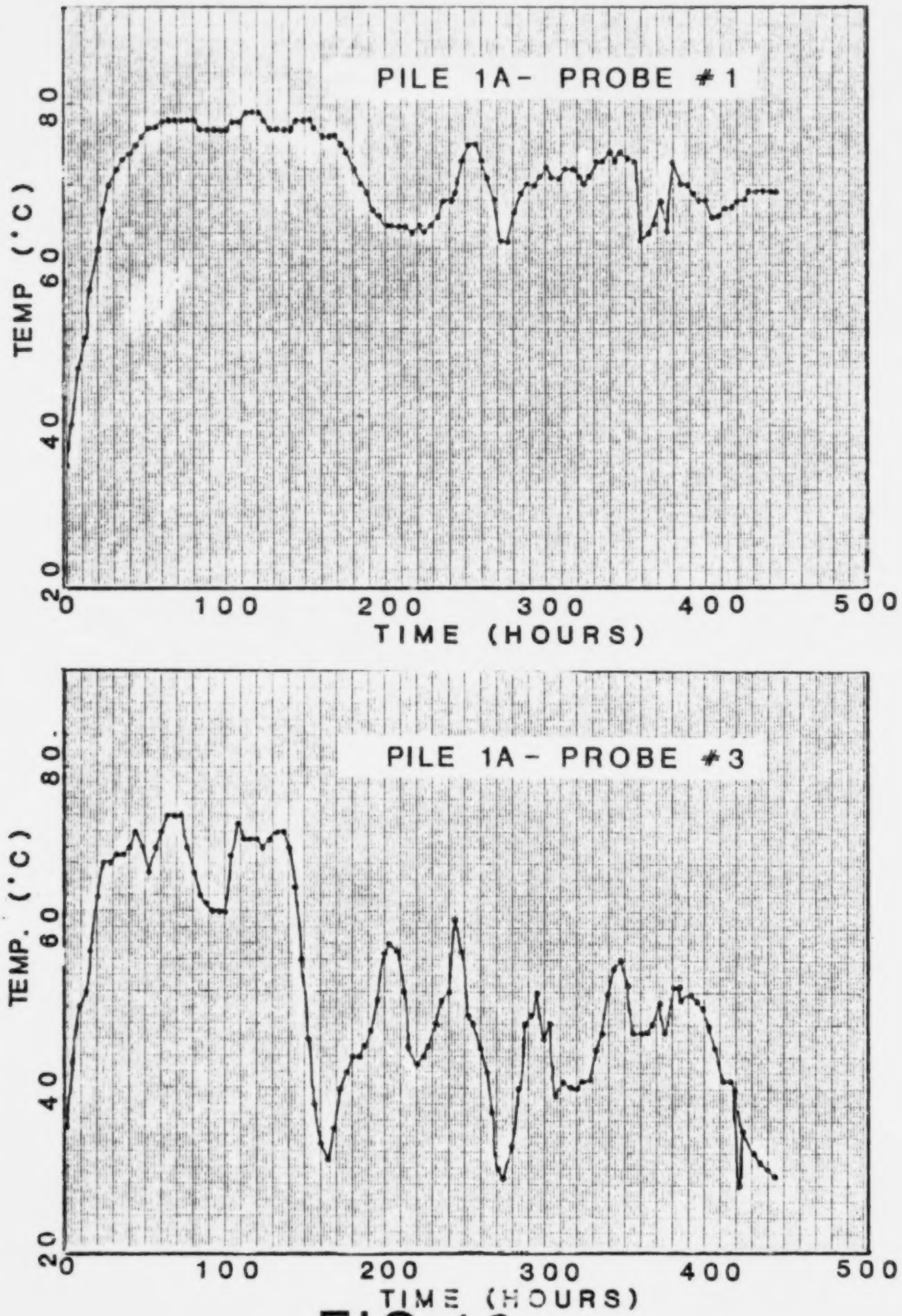


FIG 16

TEMP. VS TIME:
PILE 1A, PROBE #4,5

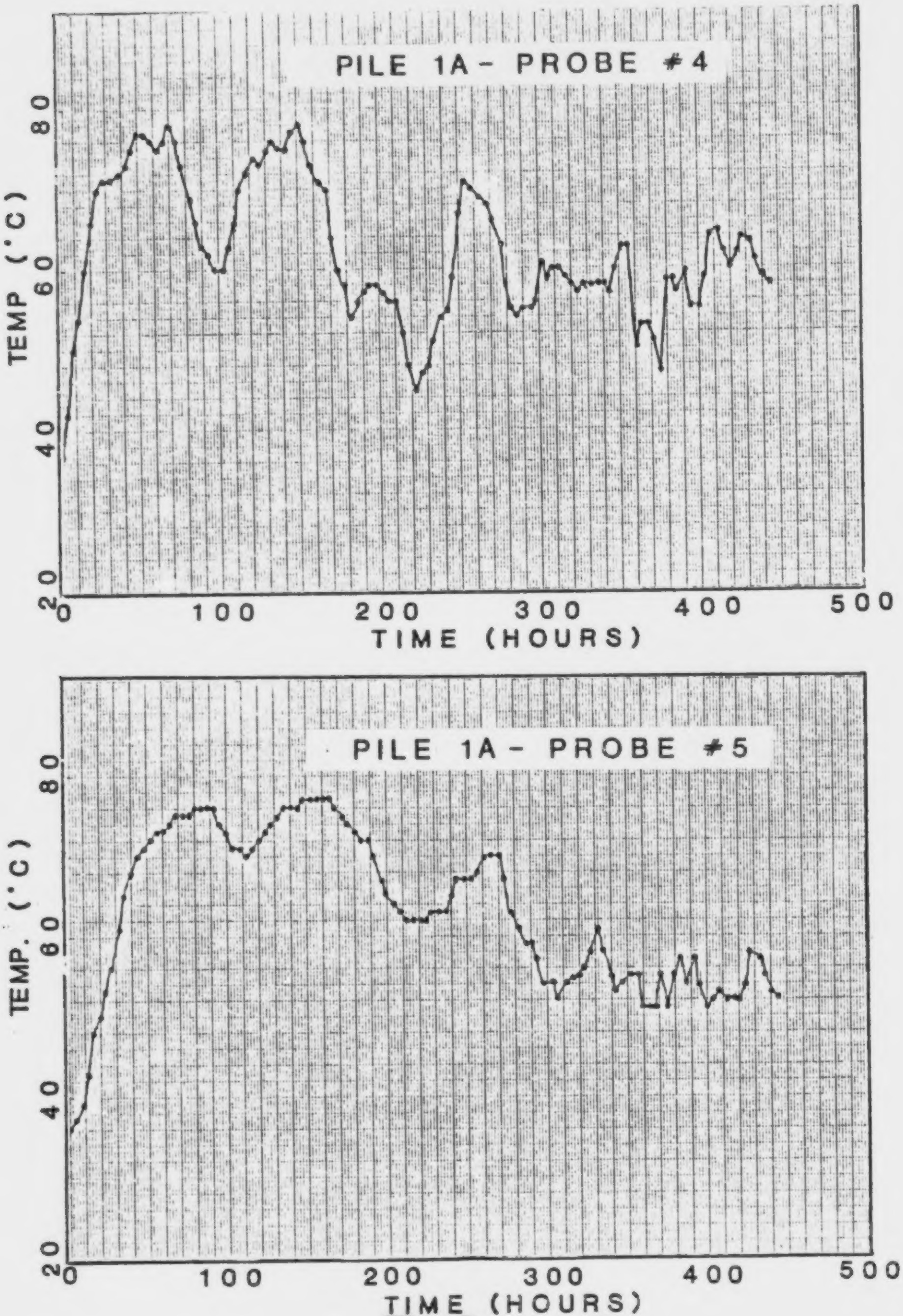


FIG 17

TEMP. VS TIME:
PILE 1B, PROBE #1,2

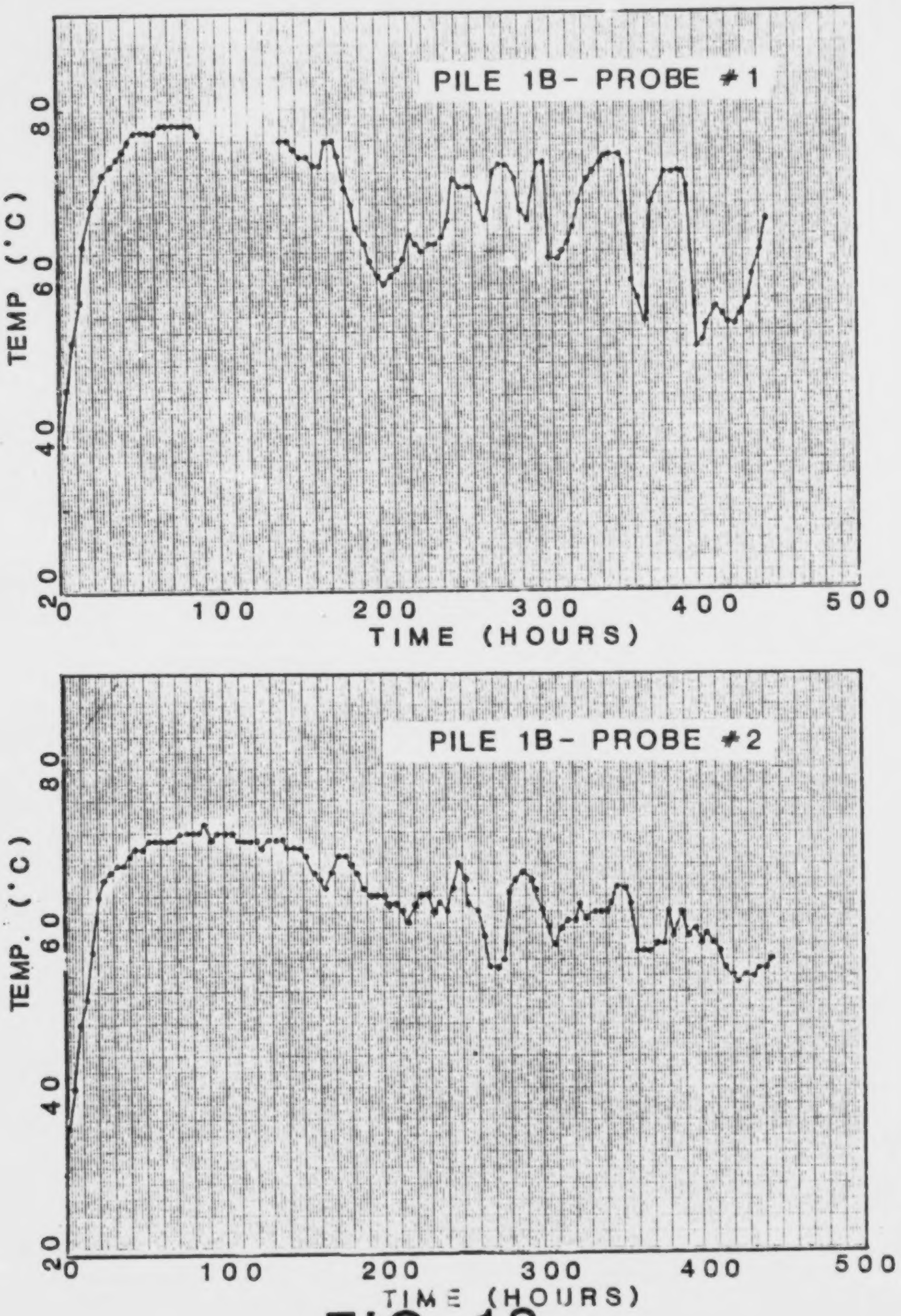


FIG 18

TEMP. VS TIME:
PILE 1B, PROBE #3, 4

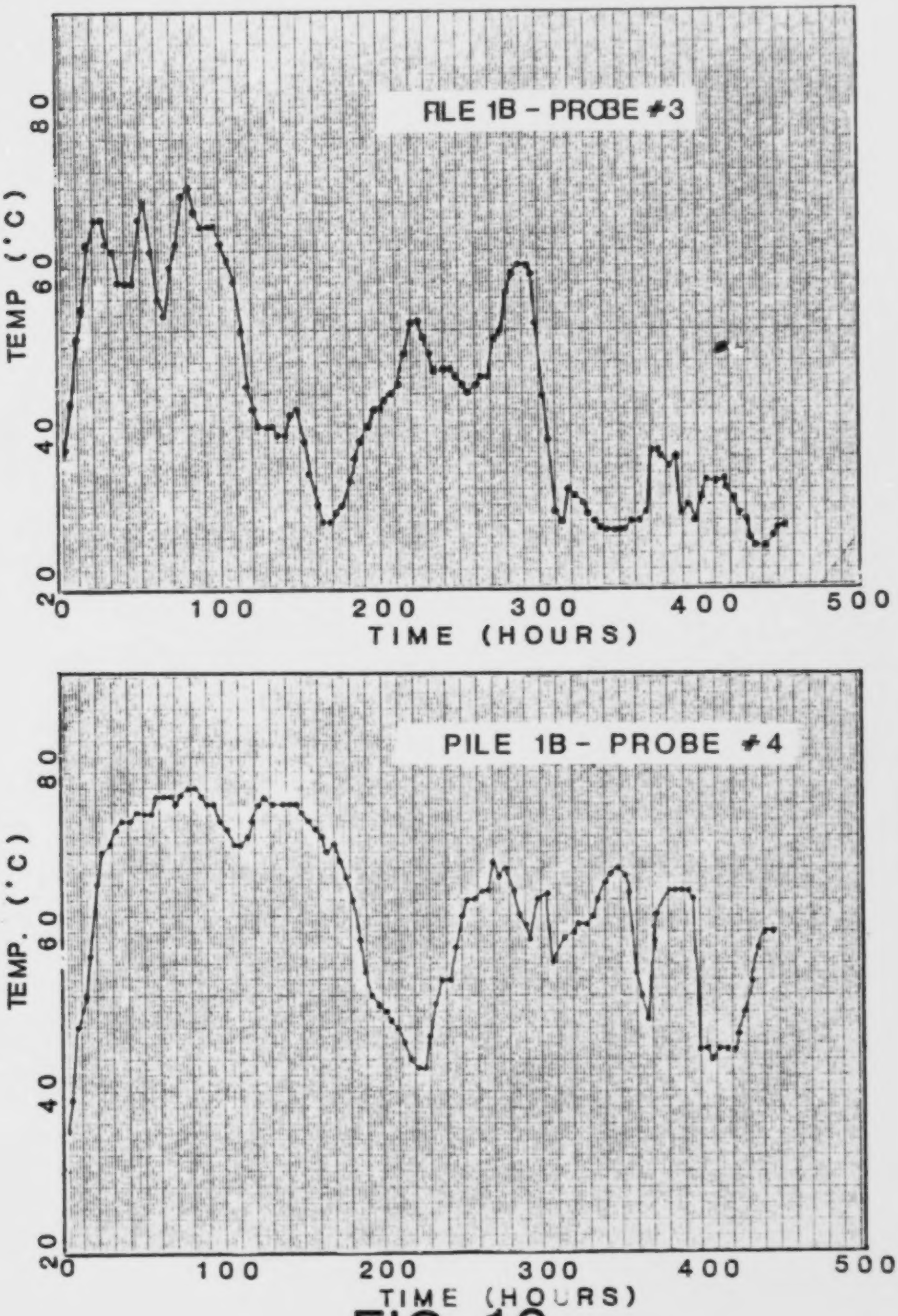


FIG 19

TEMP. VS TIME:
PILE 1B, PROBE #5

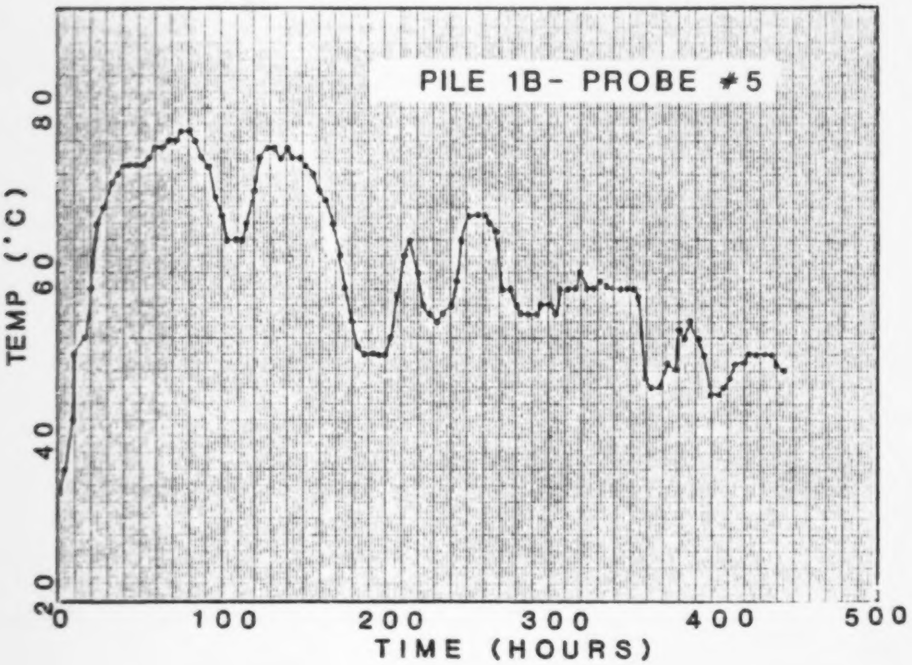


FIG 20

TEMP. VS TIME:
PILE 1C, PROBE #1,2

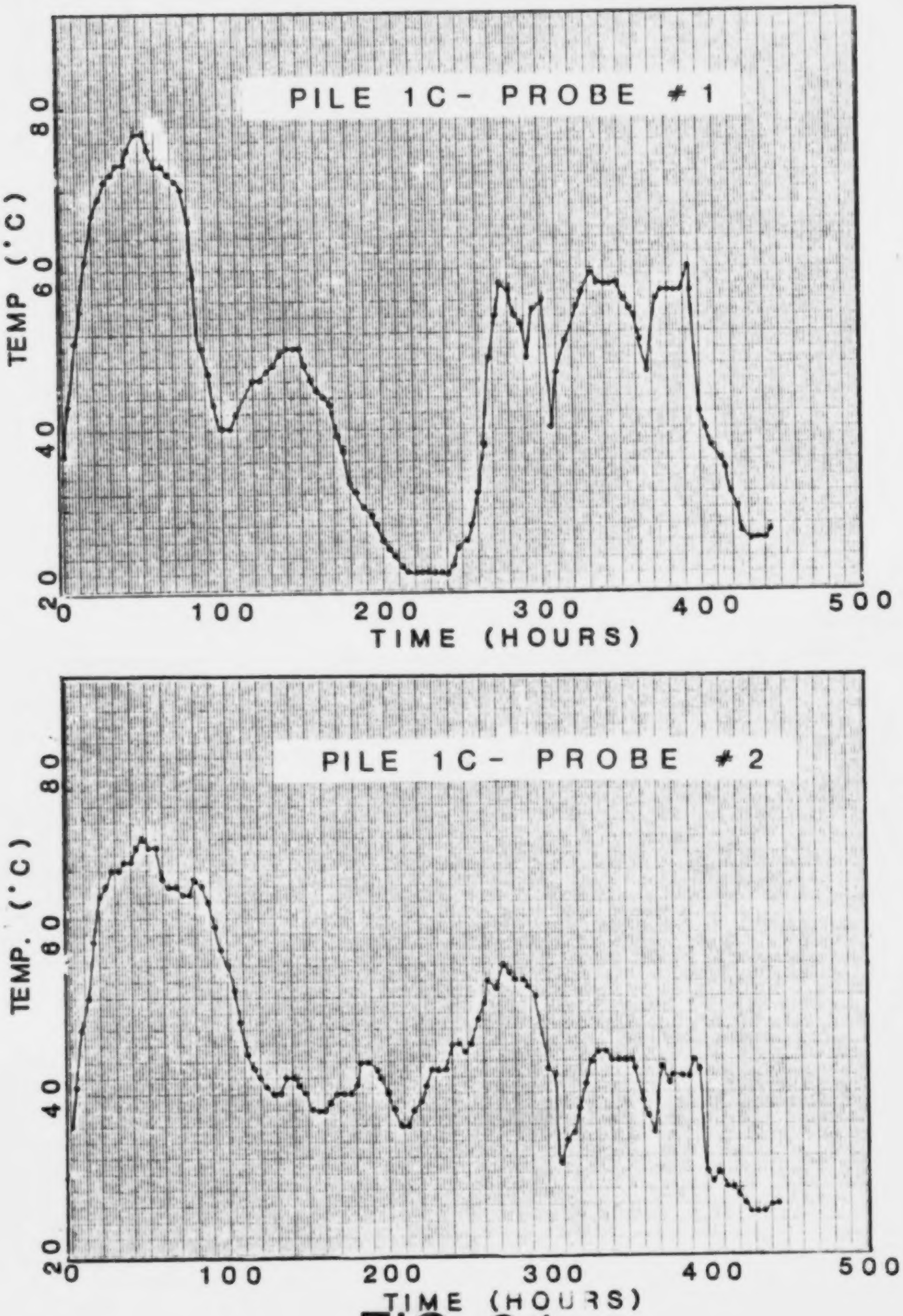


FIG 21

TEMP. VS TIME:
PILE 1C, PROBE #3,4

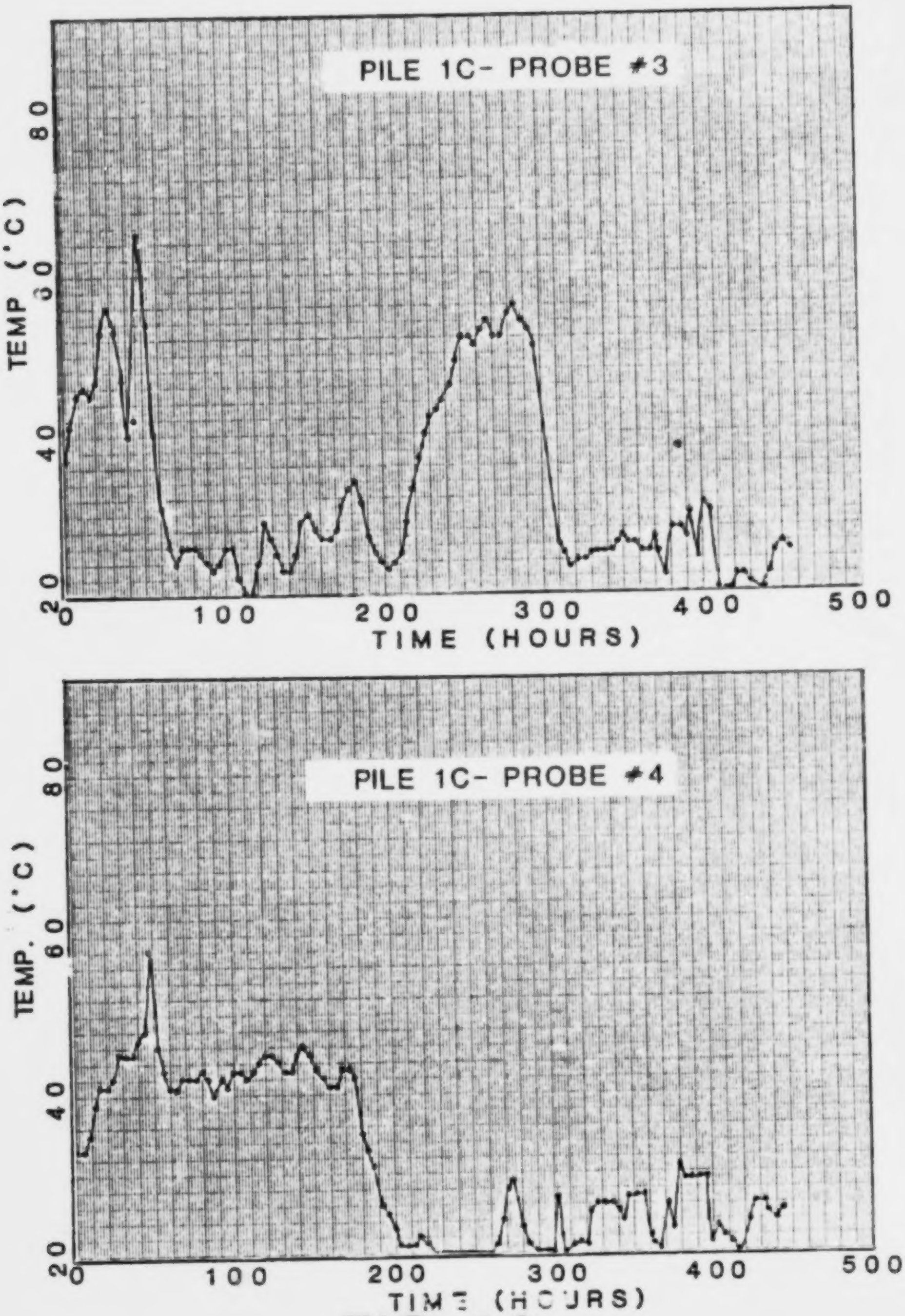


FIG 22

TEMP. VS TIME: PILE 1C, PROBE #5

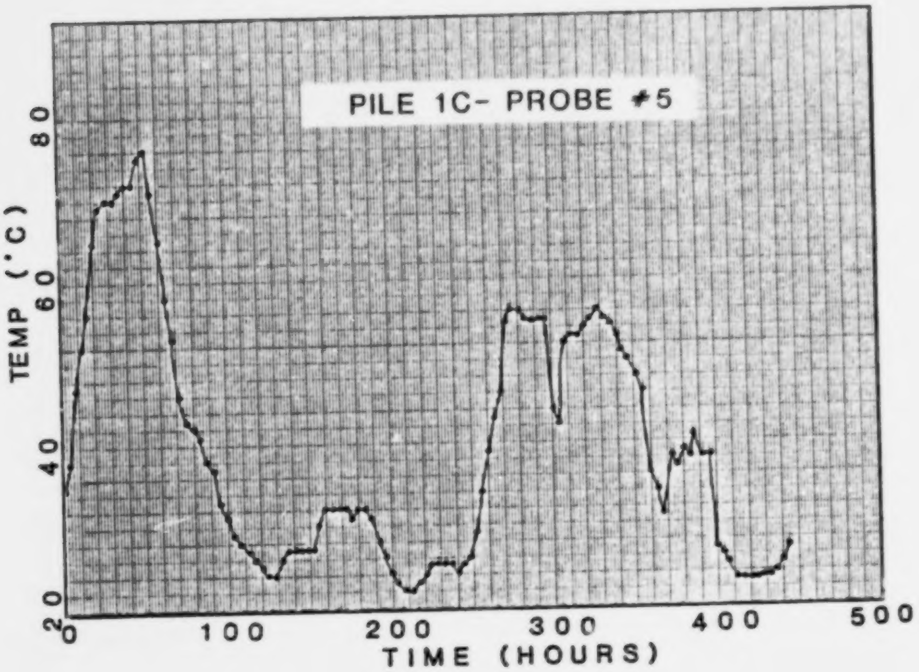


FIG 23

%CO2 VS TIME - PILE 1A, 1B

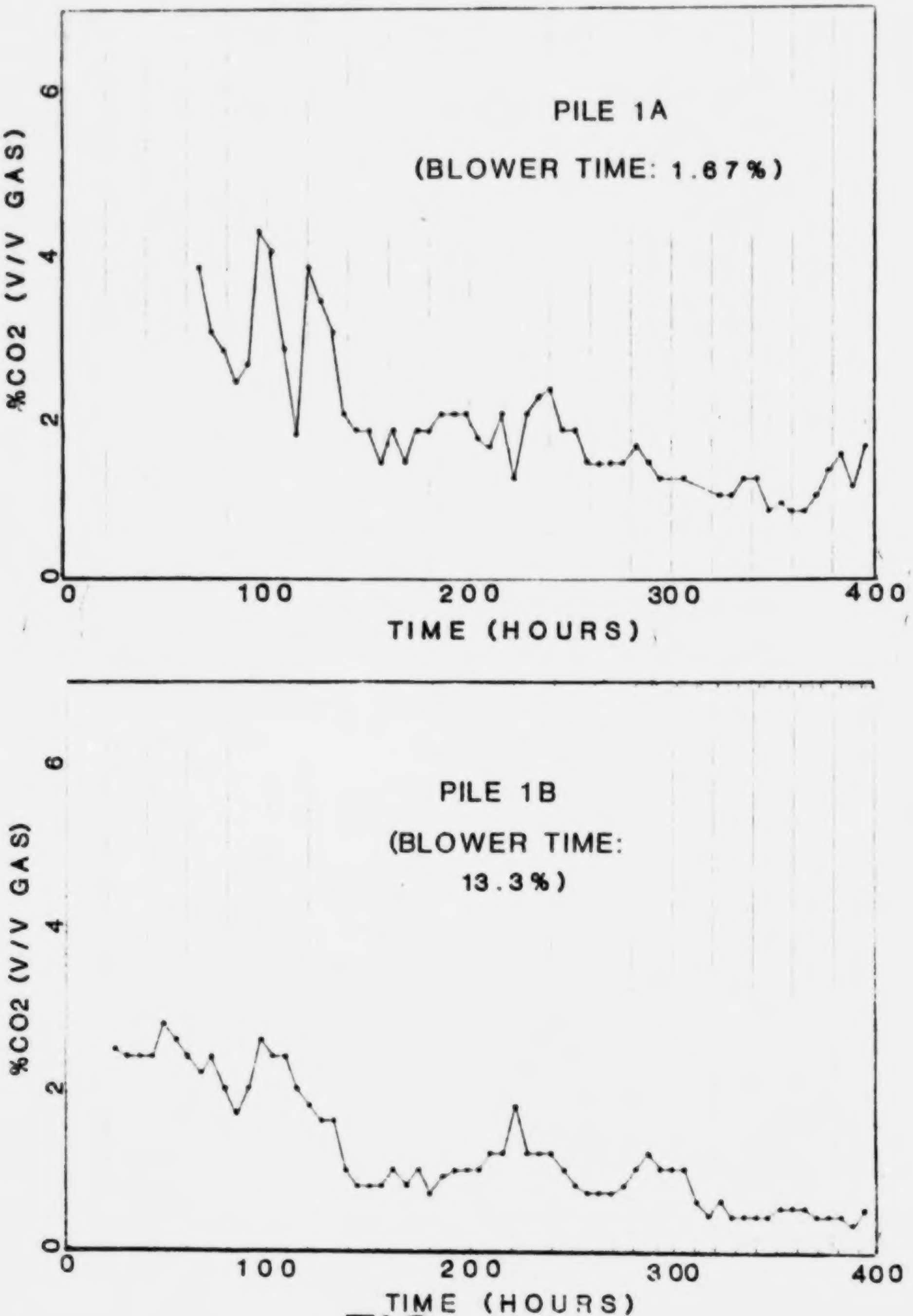


FIG 24

%CO2 VS TIME - PILE 1C

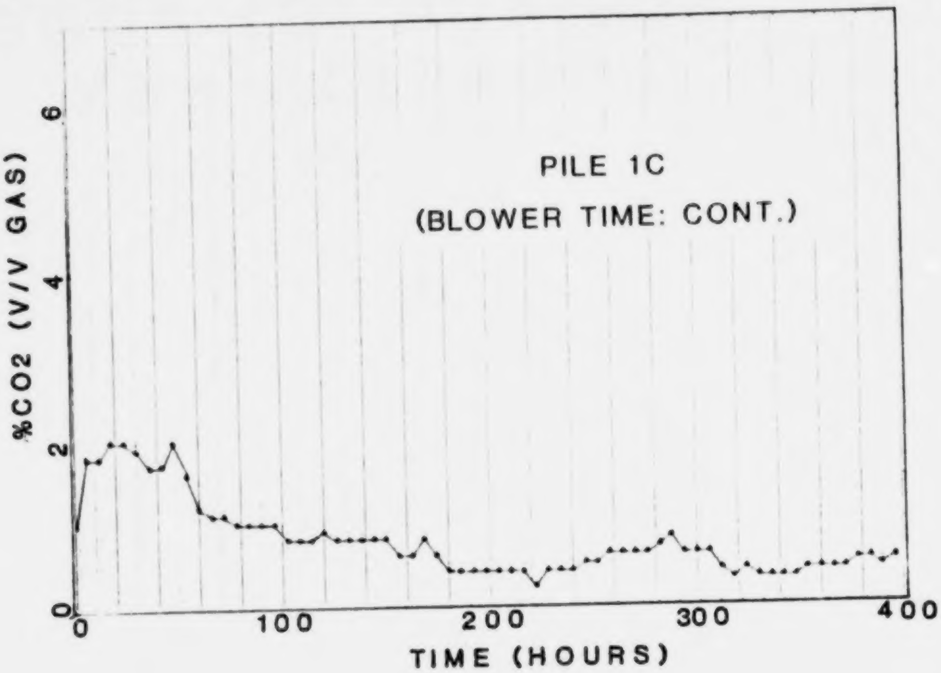
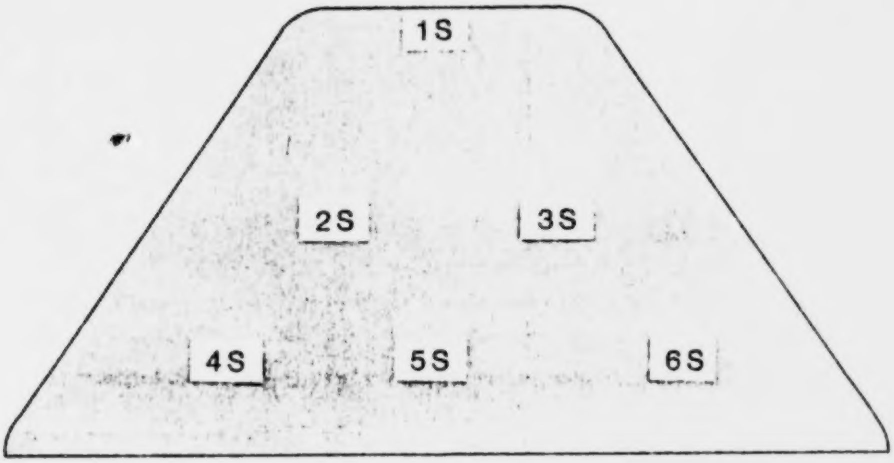


FIG 25

RUN #2 AND RUN #3 SURFACE (S) PROBE LOCATION KEY

Run #2


1S
2S
3S
4S
5S
6S

Run #3

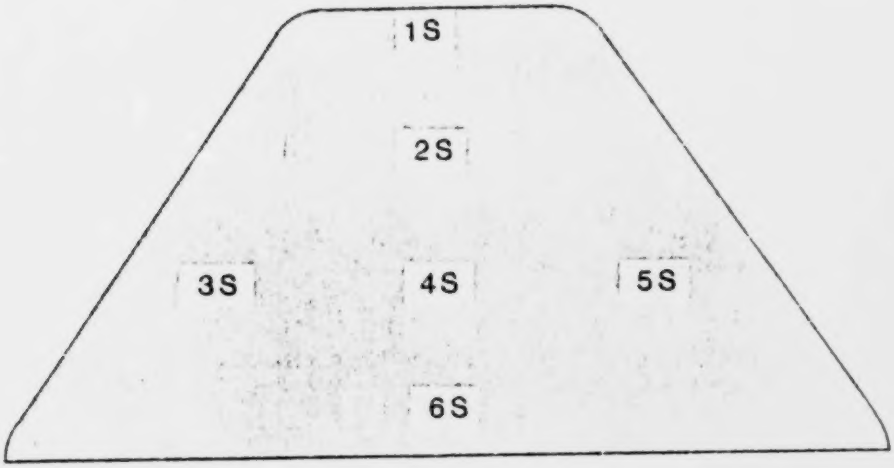

1S
2S
3S
4S
5S
6S

FIGURE 26

TEMP. VS TIME
PILE 2A,PROBE 11,21

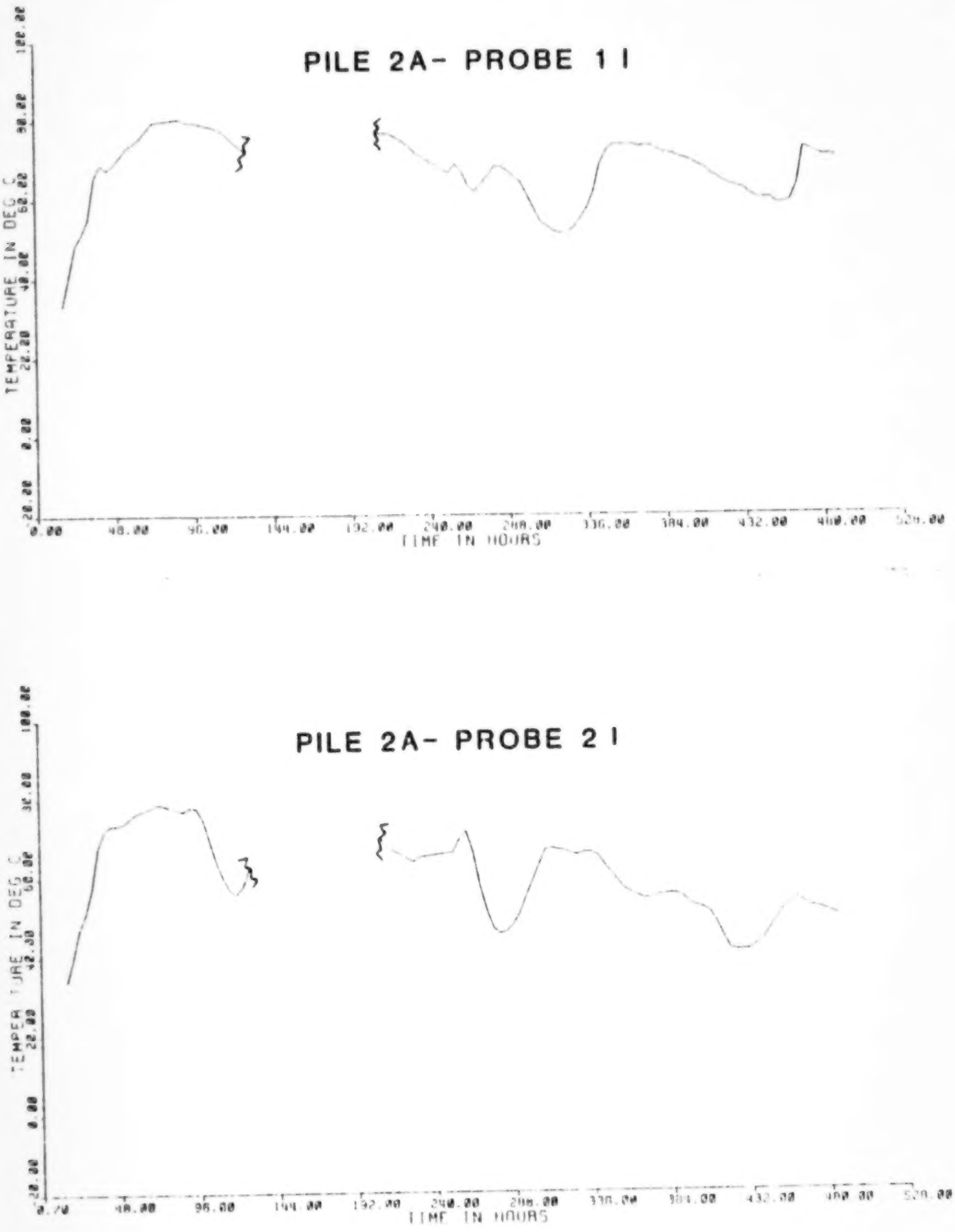


FIGURE 27

TEMP. VS TIME
PILE 2A, PROBE 41

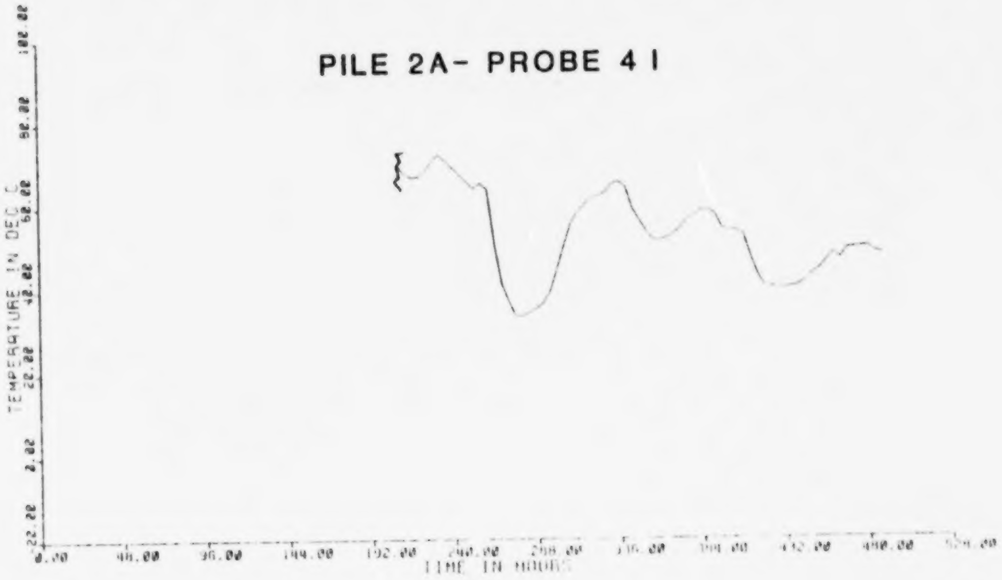


FIGURE 28

TEMP. VS TIME
PILE 2B, PROBE 1I, 2I

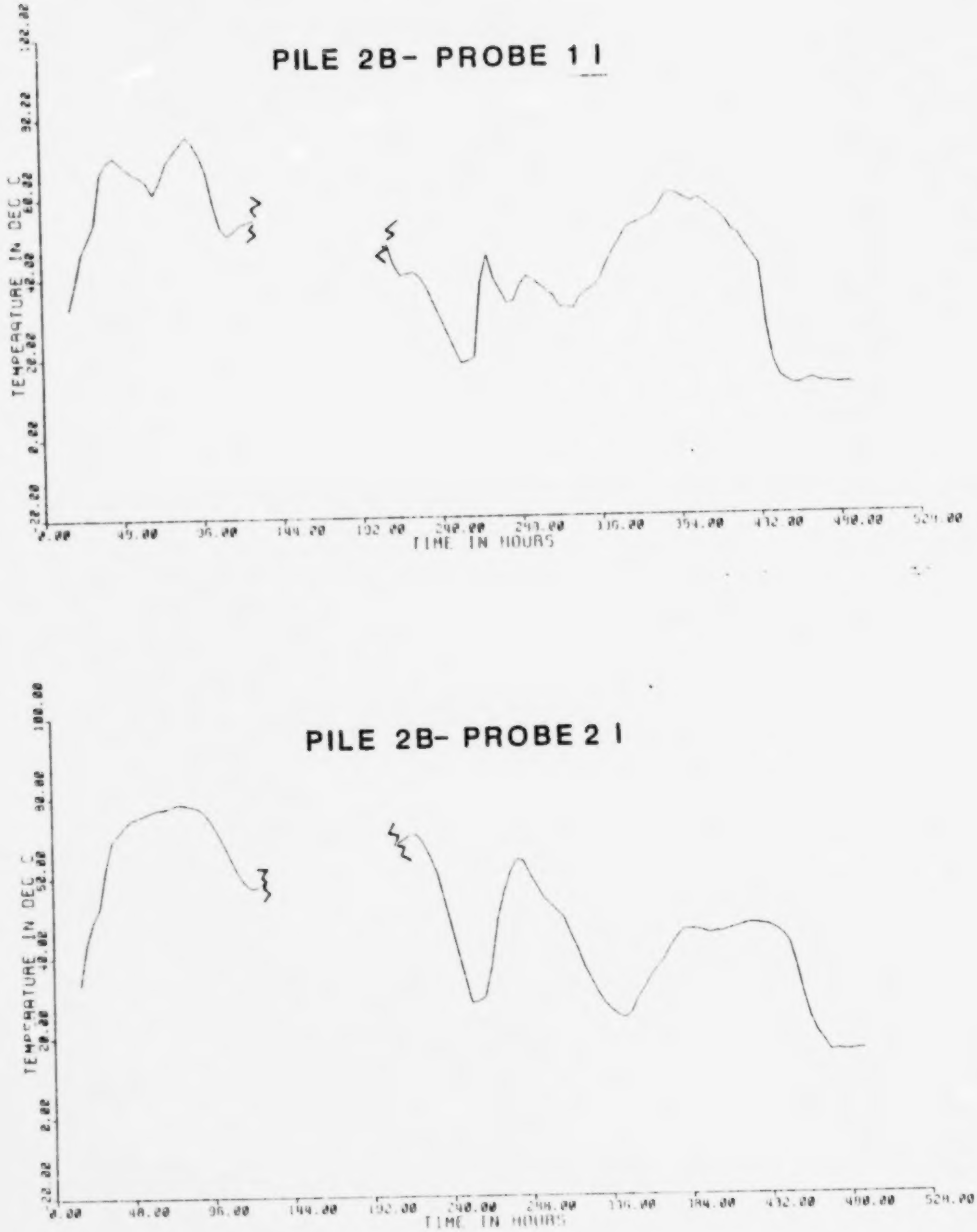
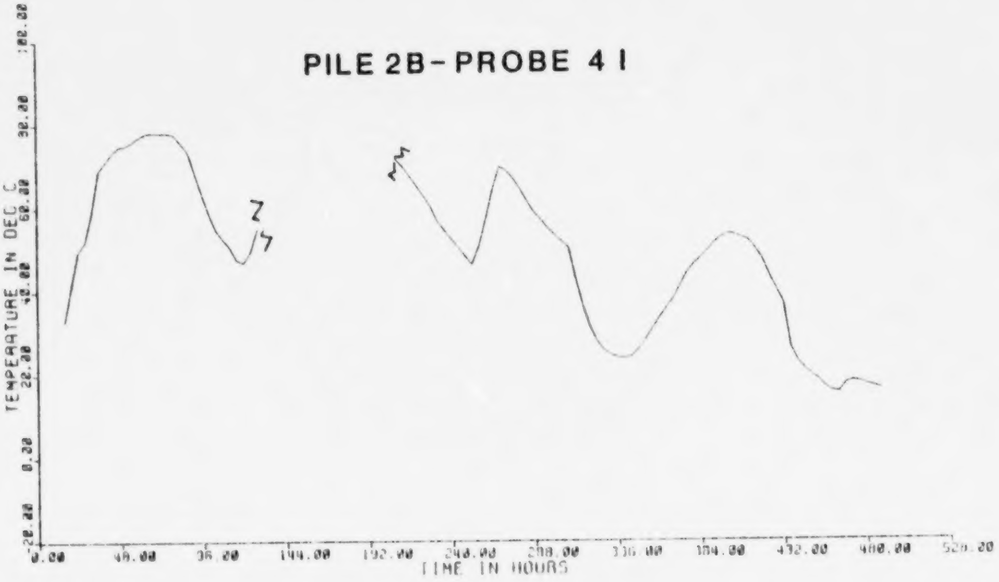


FIGURE 29

TEMP. VS TIME
PILE 2B, PROBE 41,51



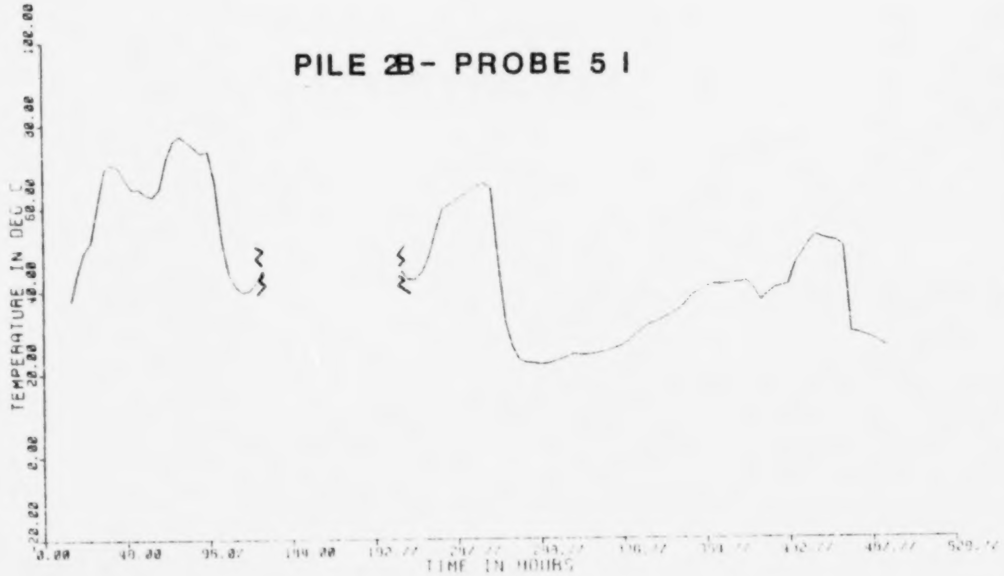


FIGURE 30

TEMP. VS TIME
PILE2C,PROBE1I,2I

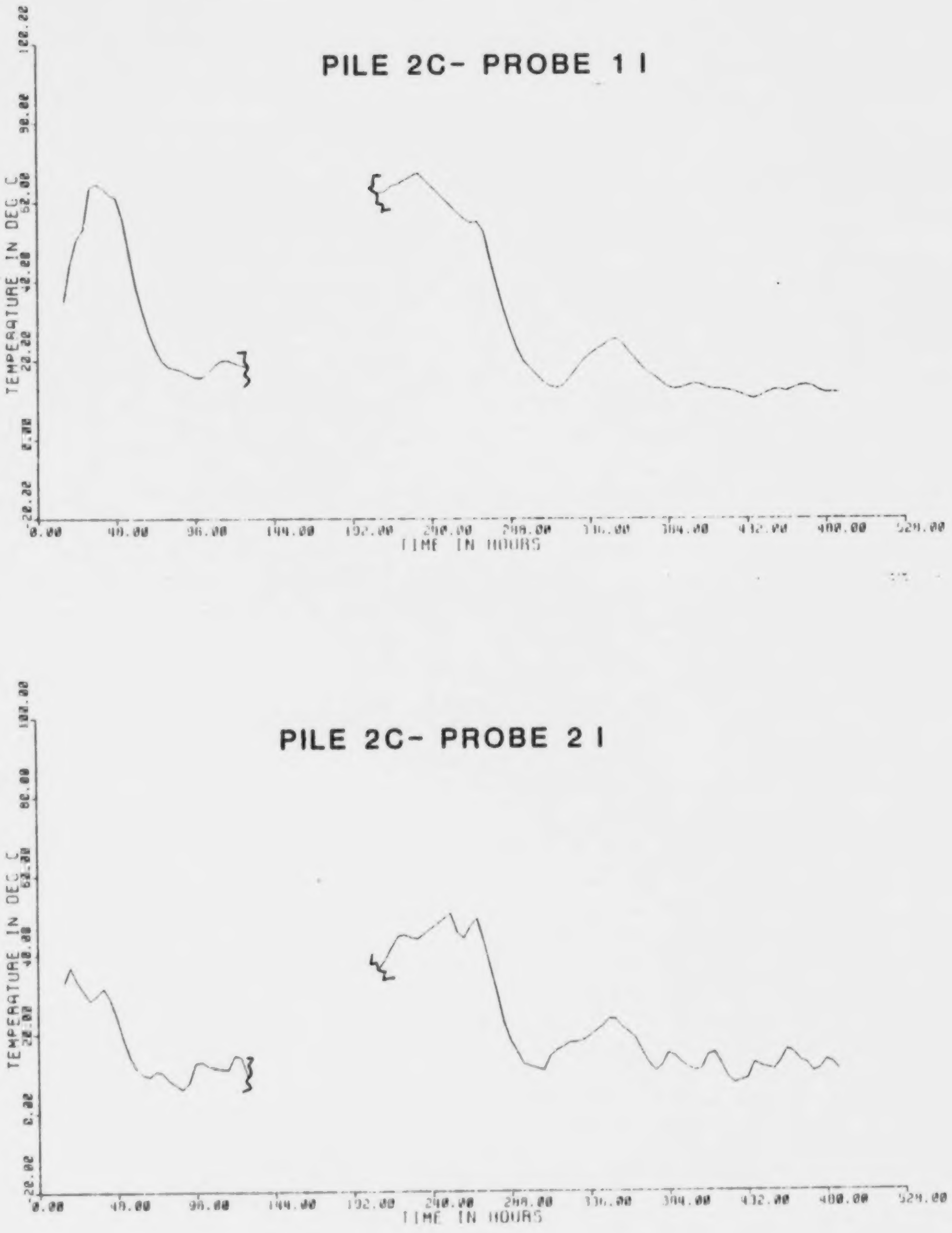


FIGURE 31

TEMP. VS TIME
PILE 2C,PROBE 3I,4I

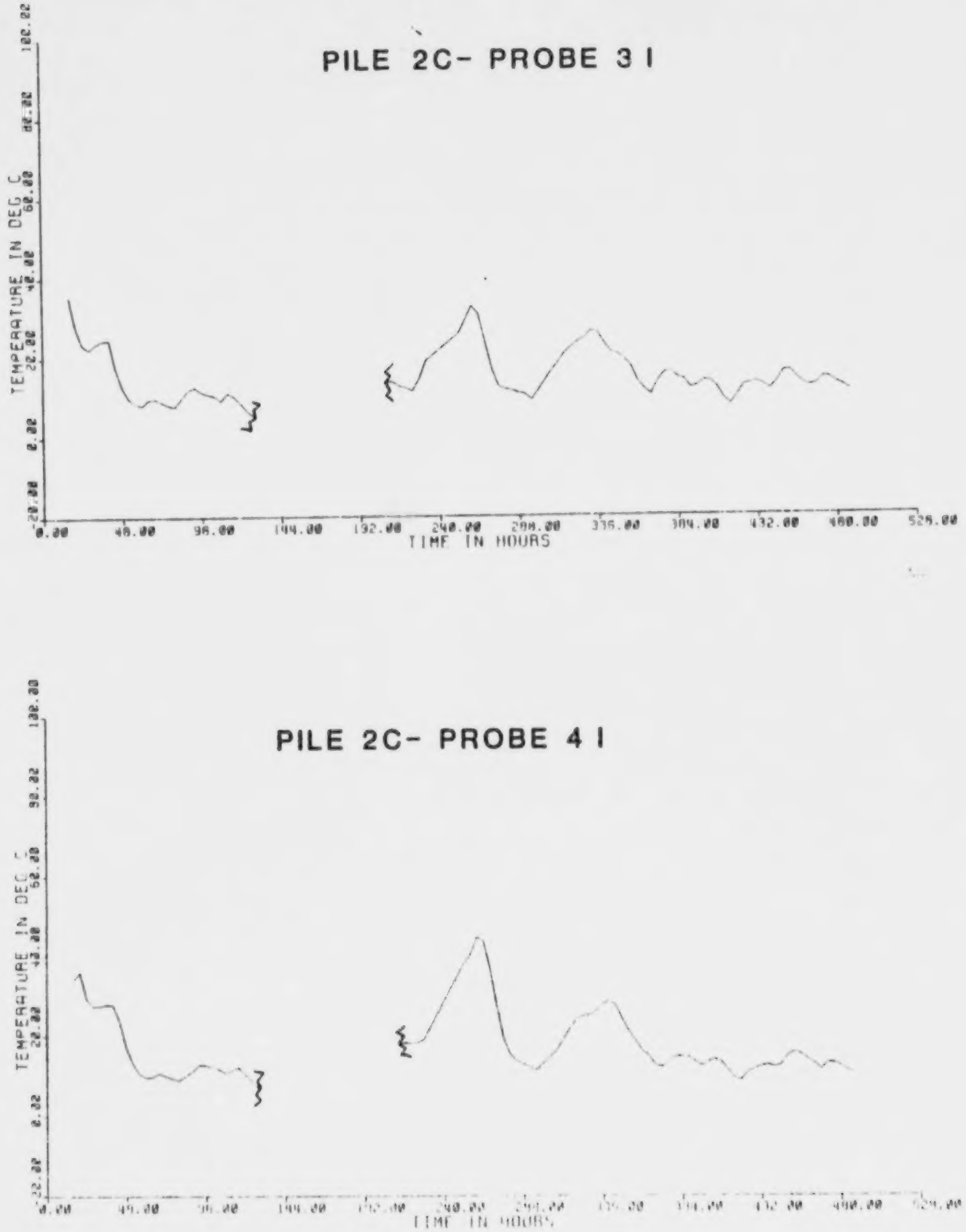


FIGURE 32

TEMP. VS TIME
PILE2C,PROBE 5I

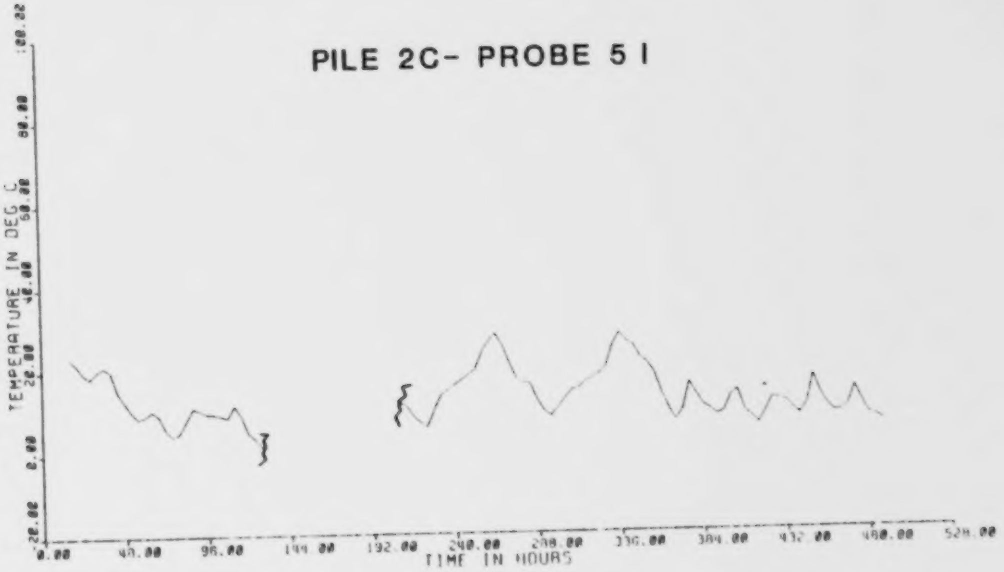


FIGURE 33

TEMP. VS TIME
PILE2A,PROBE 1S,2S

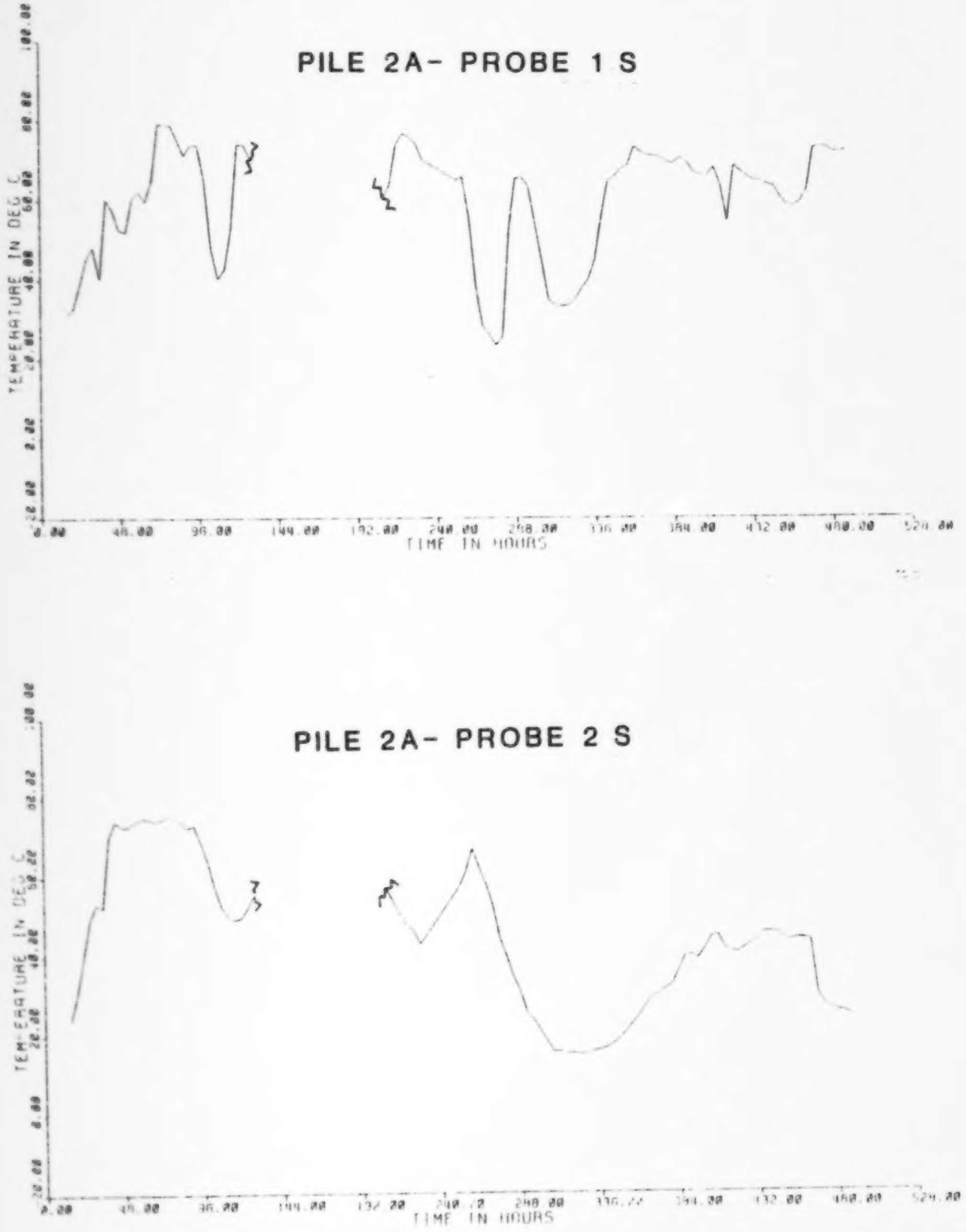


FIGURE 34

TEMP. VS TIME
PILE 2A, PROBE 3S, 5S

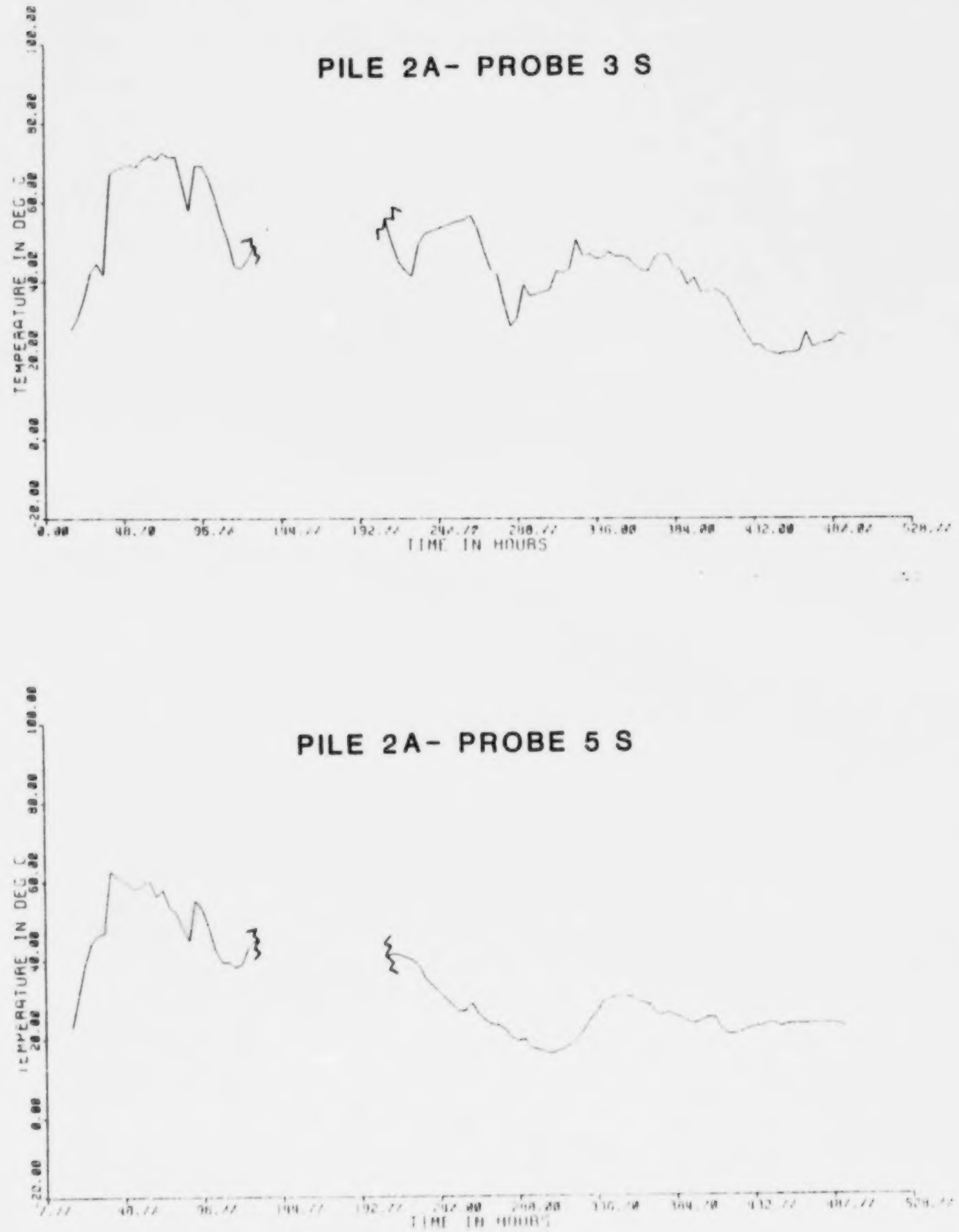


FIGURE 35

TEMP. VS TIME
PILE 2A,PROBE 6S

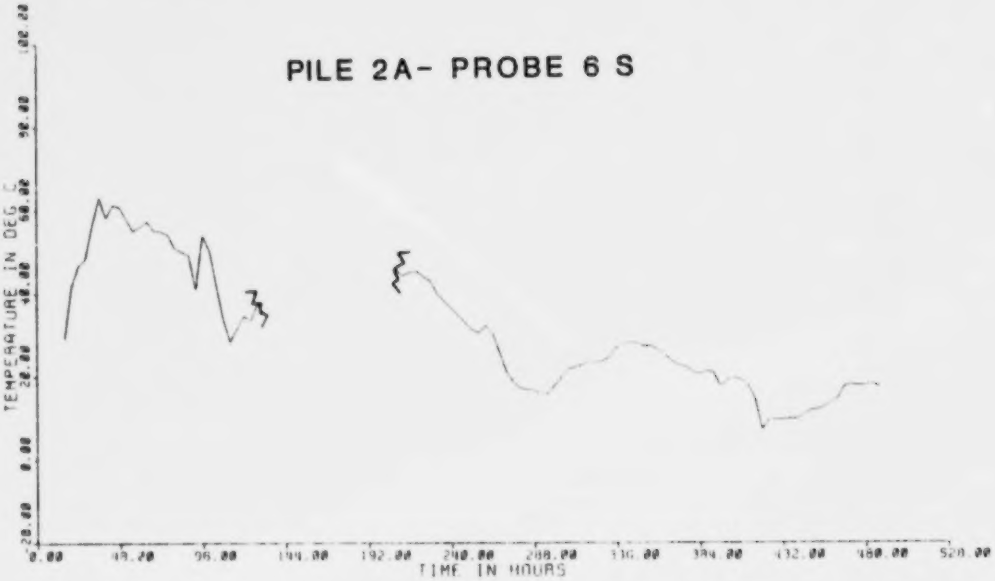
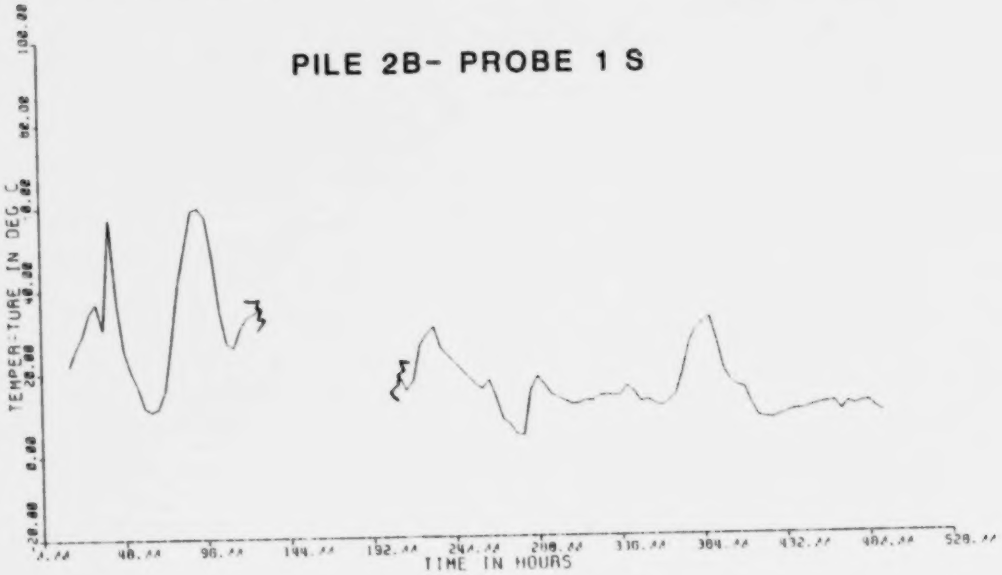


FIGURE 36

TEMP. VS TIME
PILE 2B, PROBE 1S, 2S



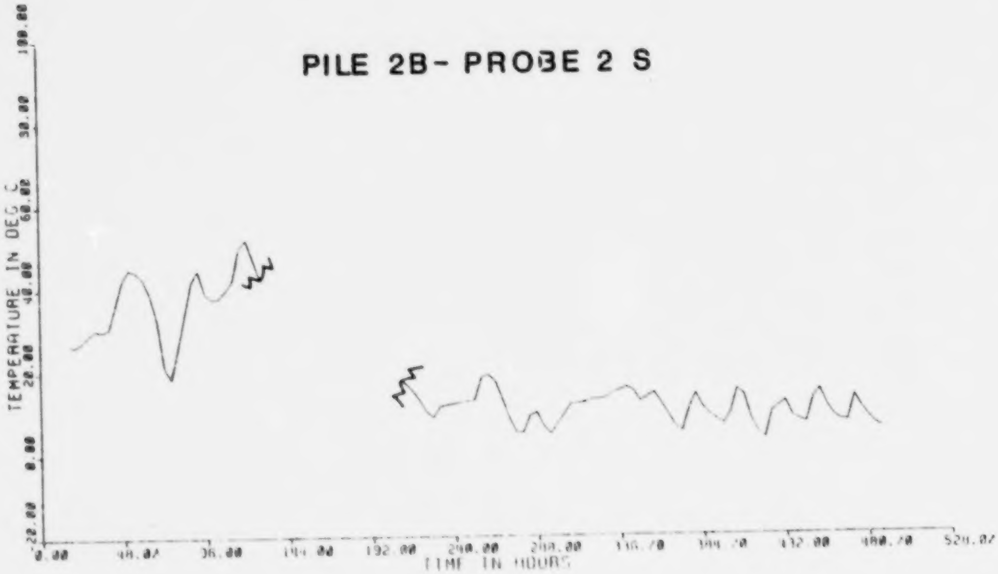


FIGURE 37

TEMP. VS TIME
PILE 2B, PROBE 3S,4S

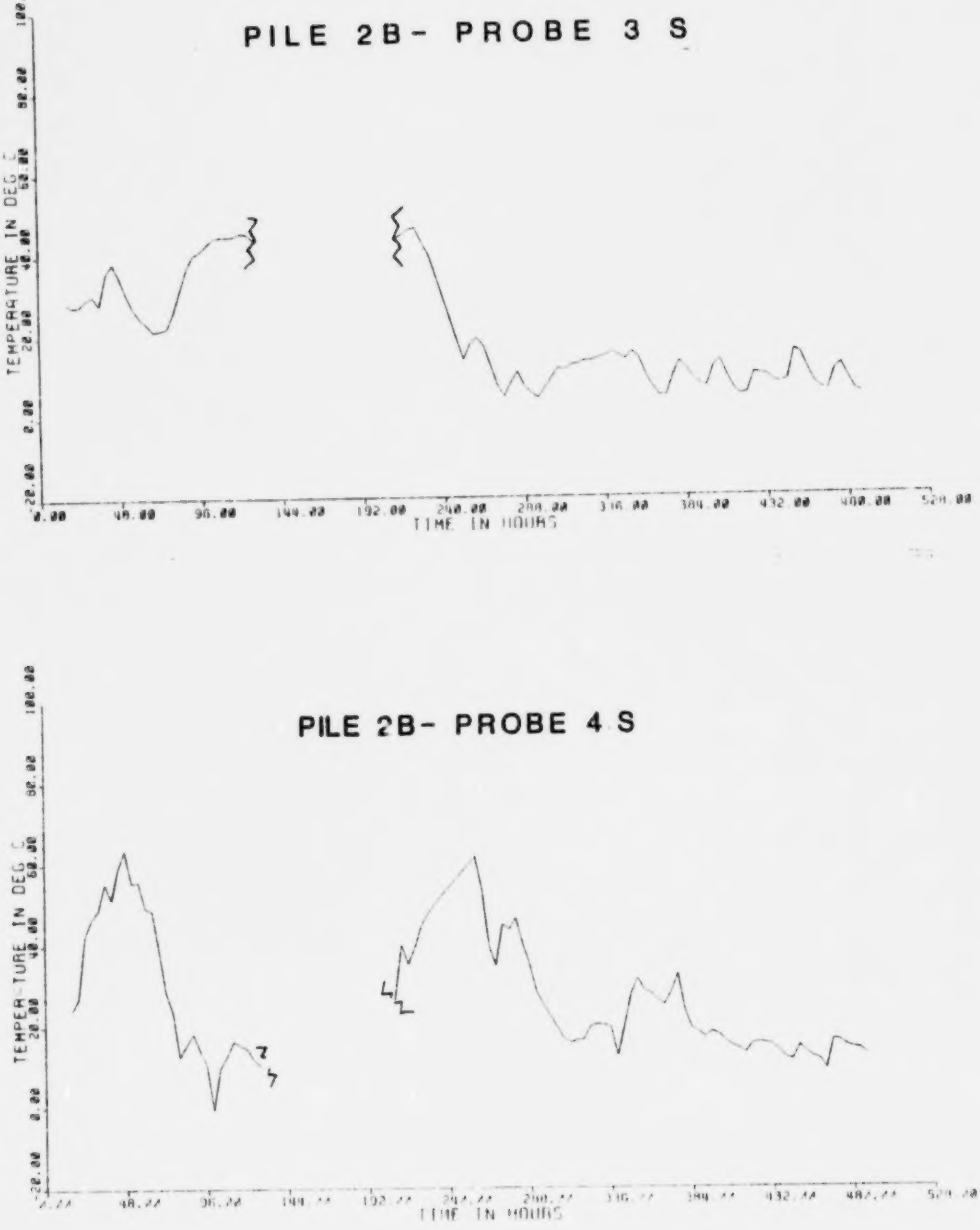


FIGURE 38

TEMP. VS TIME
PILE 2B, PROBE 5S, 6S

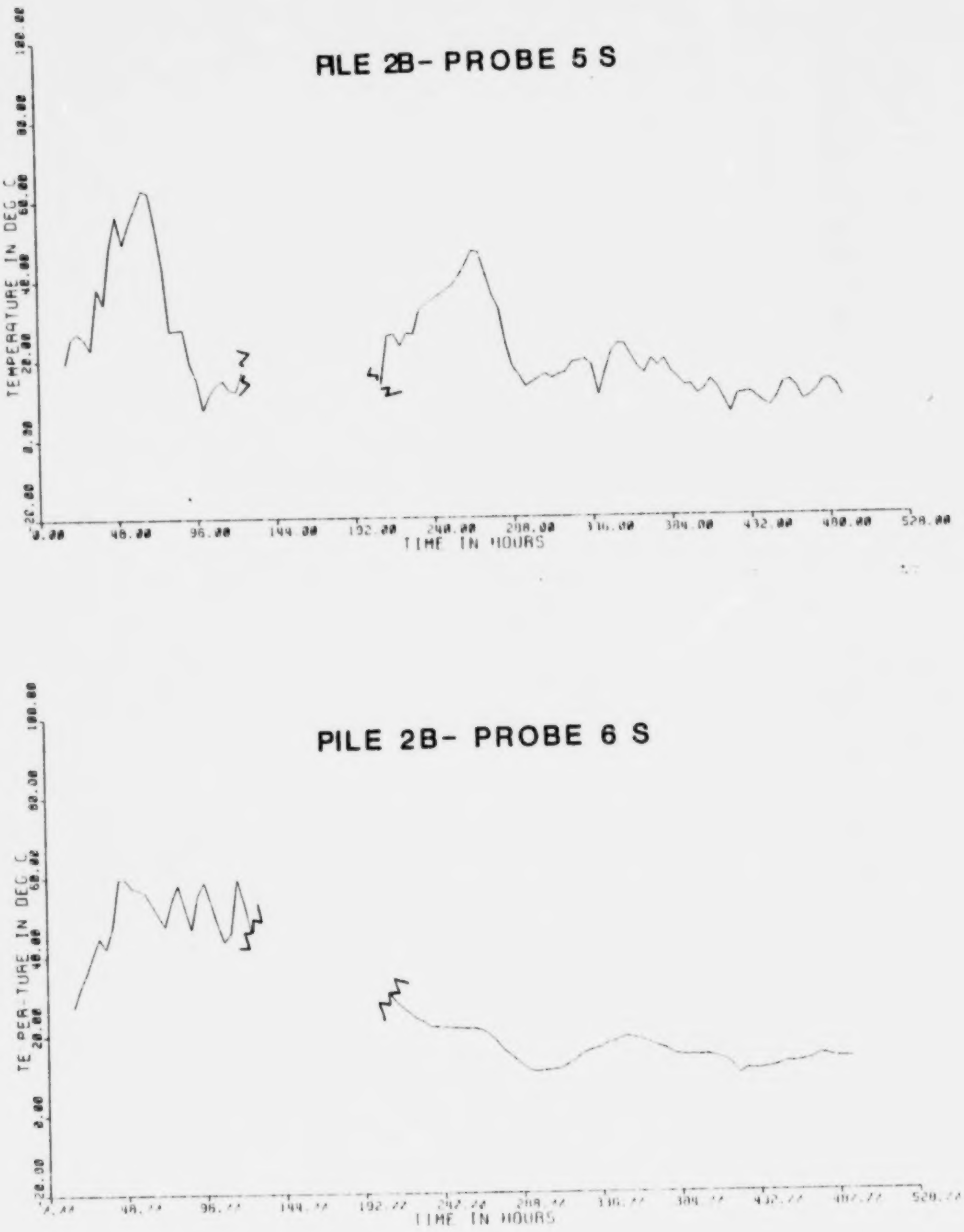


FIGURE 39

TEMP. VS TIME
PILE2C,PROBE1S,2S

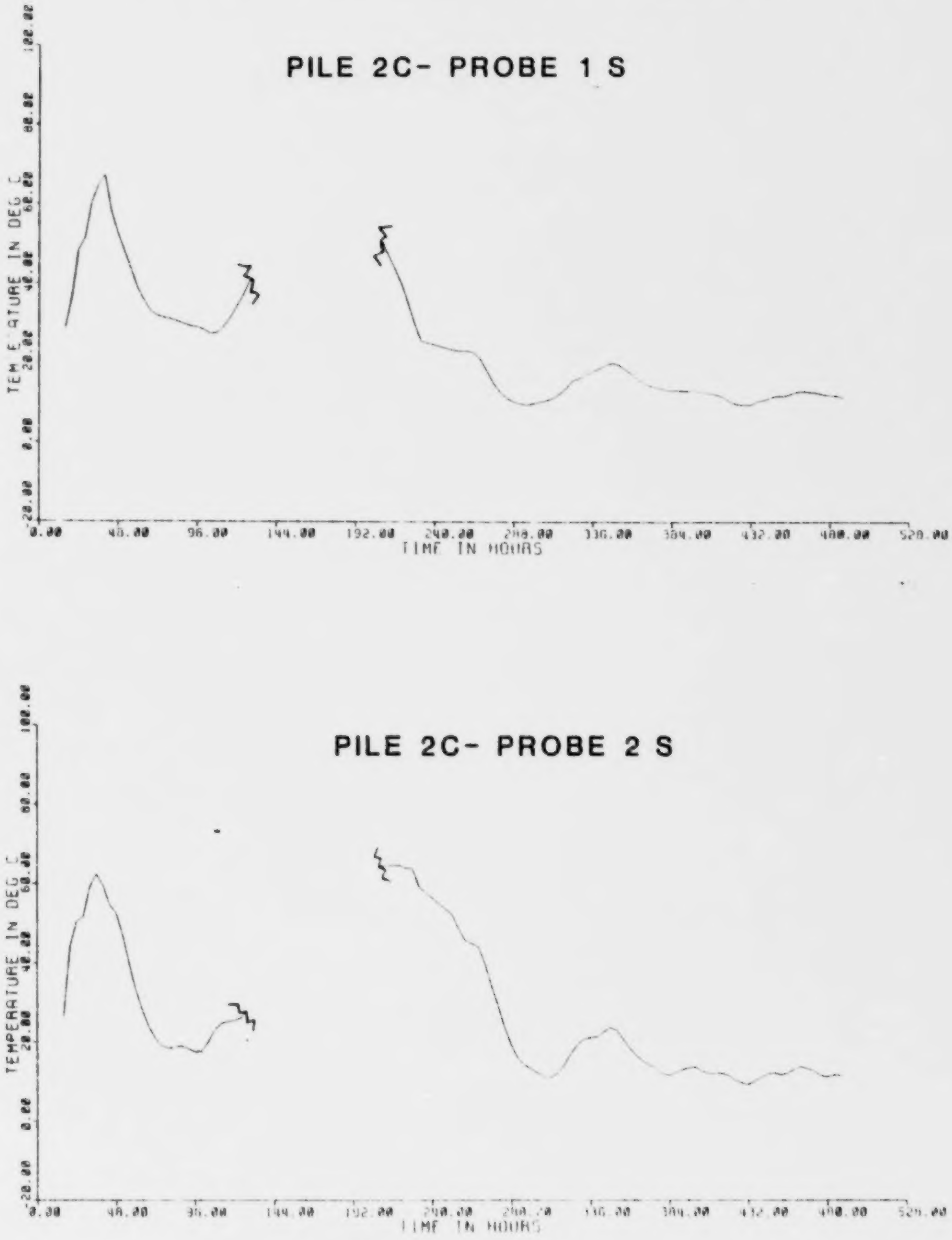


FIGURE 40

TEMP. VS TIME
PILE2C,PROBE 3S,4S

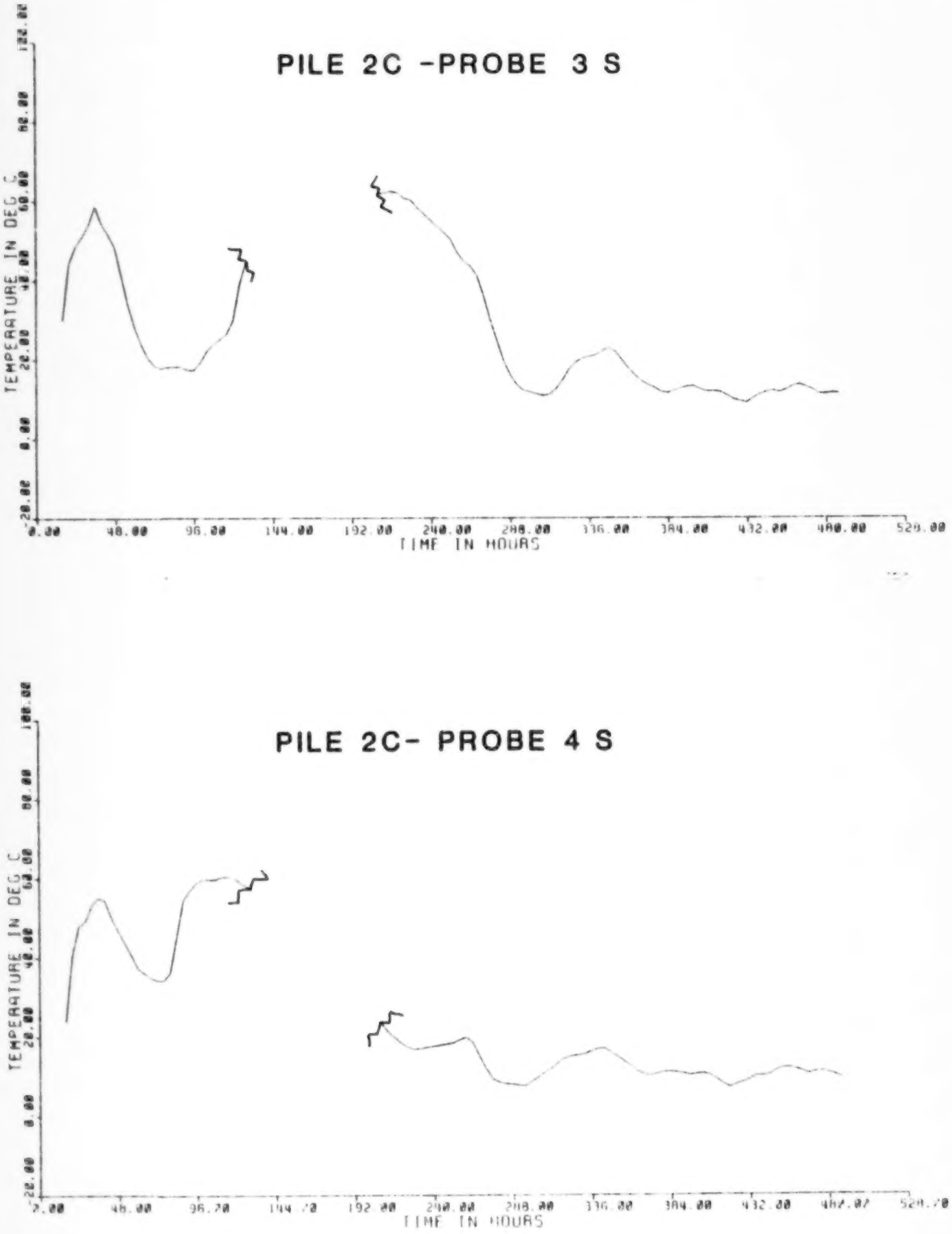


FIGURE 41

TEMP. VS TIME
PILE2C,PROBE5S,6S

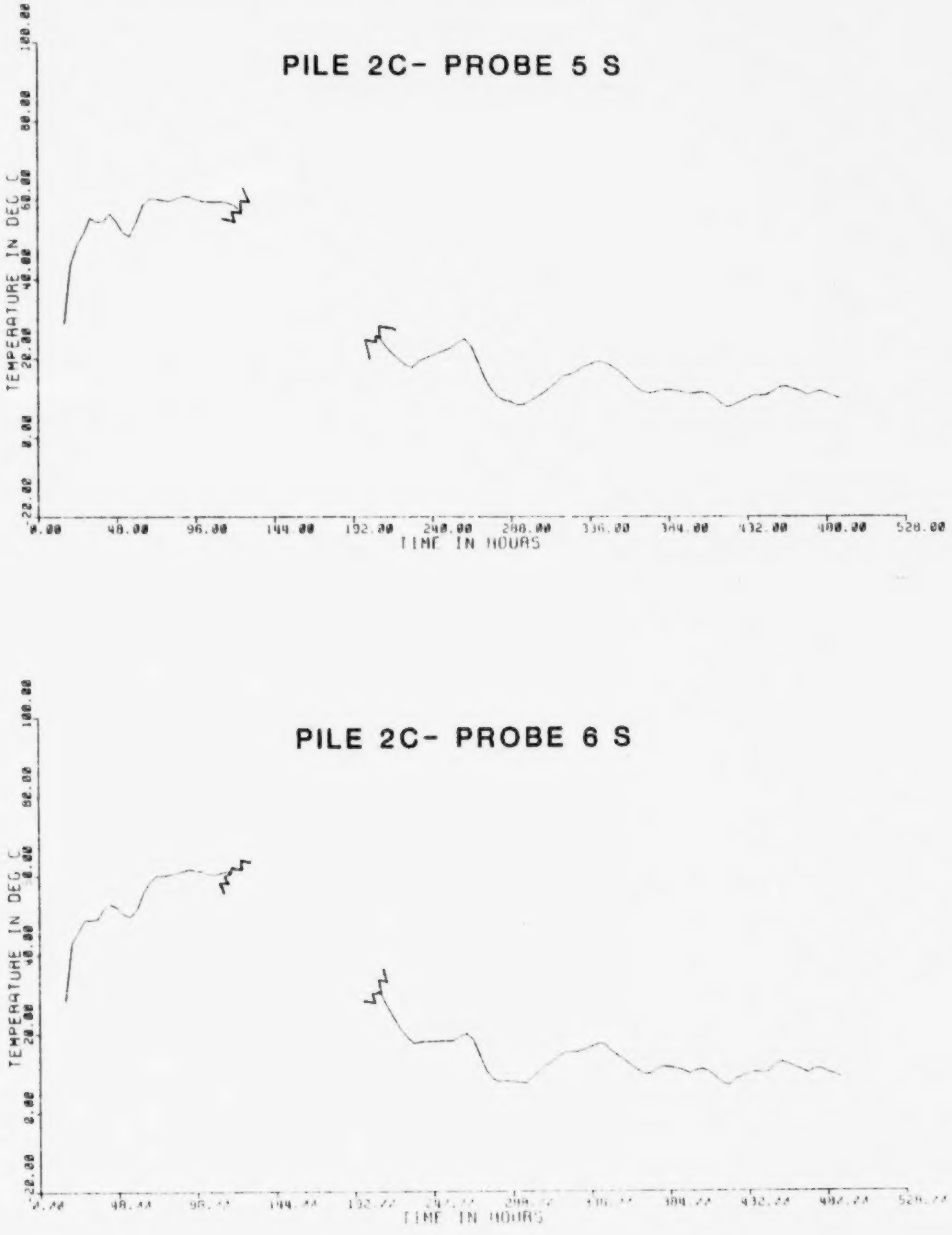


FIGURE 42

% CO2 VS TIME-PILE 2A,2B

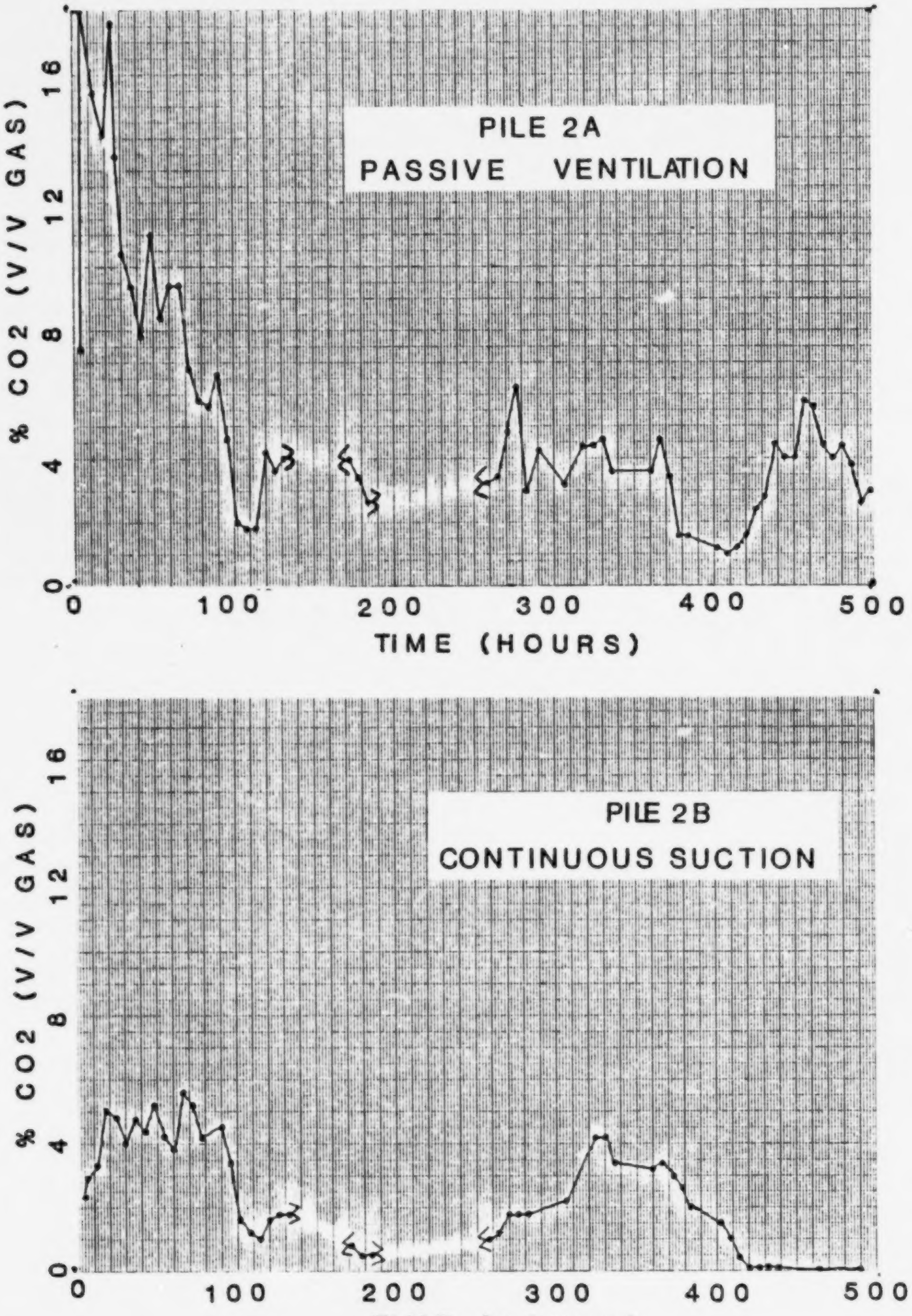


FIG 43

% CO2 VS TIME-PILE 2C

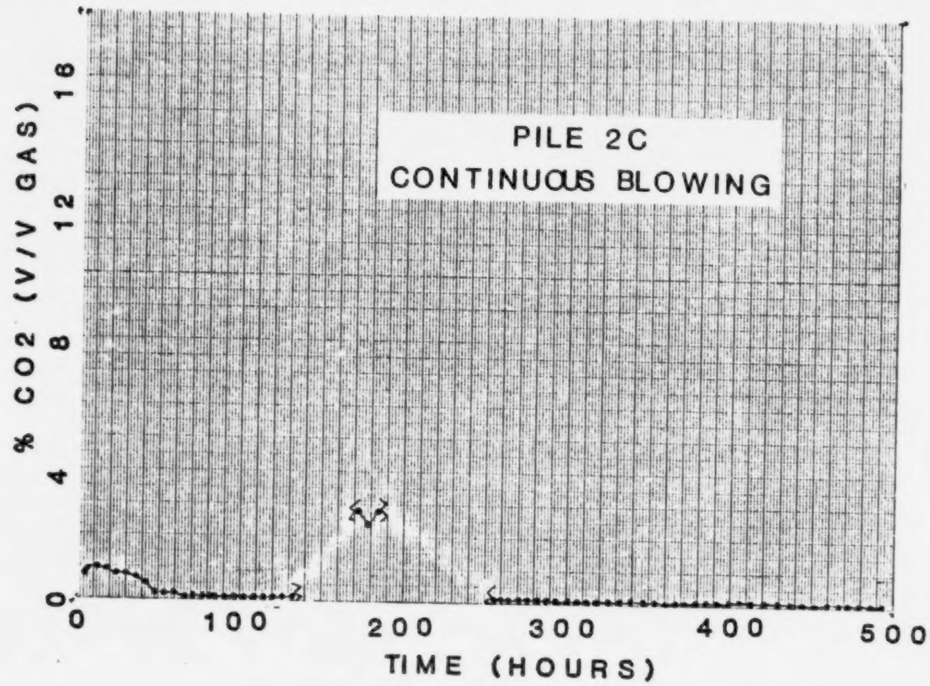


FIG 44

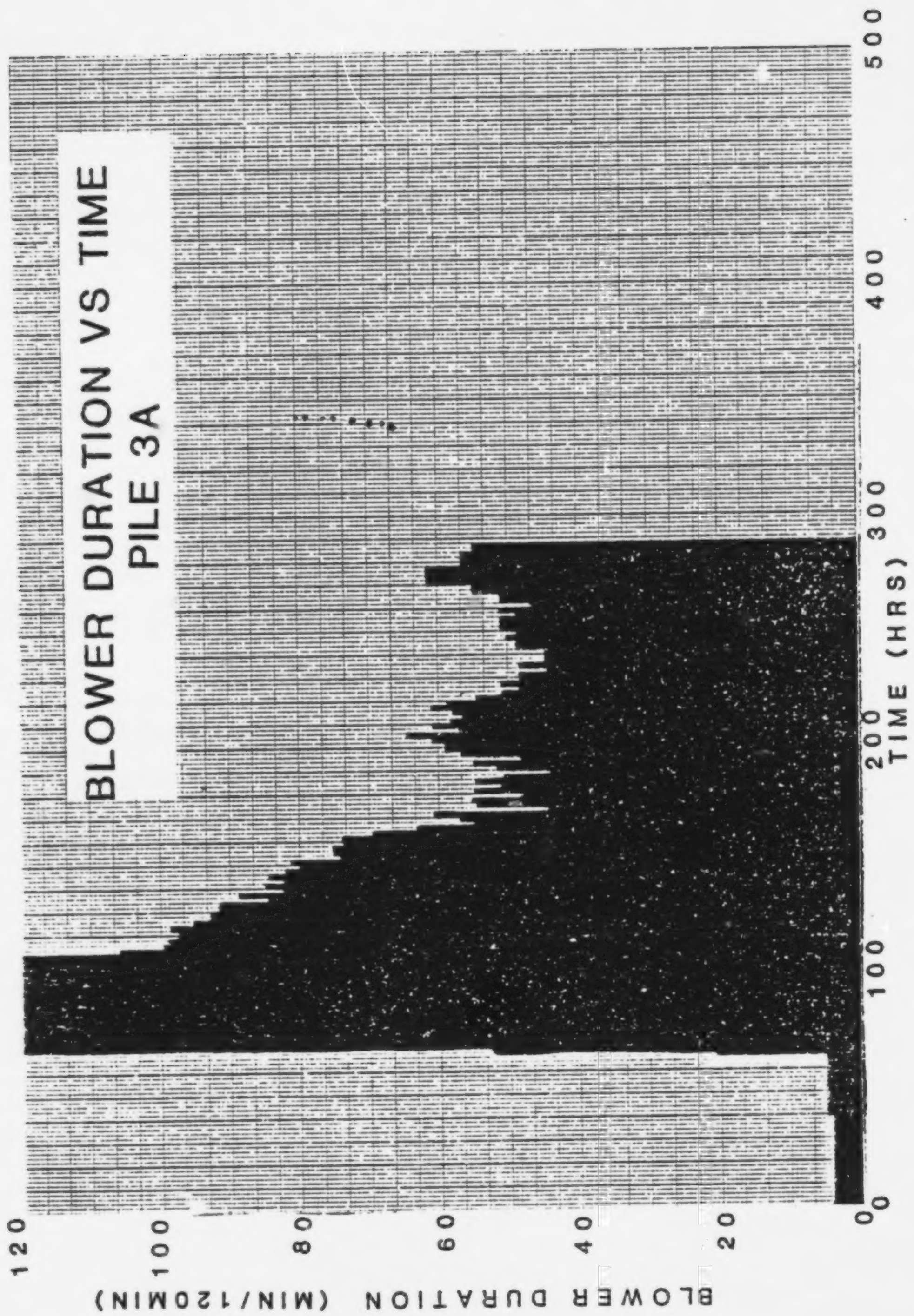

BLOWER DURATION VS TIME
PILE 3A
BLOWER DURATION (MIN/120MIN)
120
100
80
60
40
20
0
TIME (HRS)
0
100
200
300
400
500

FIG 45

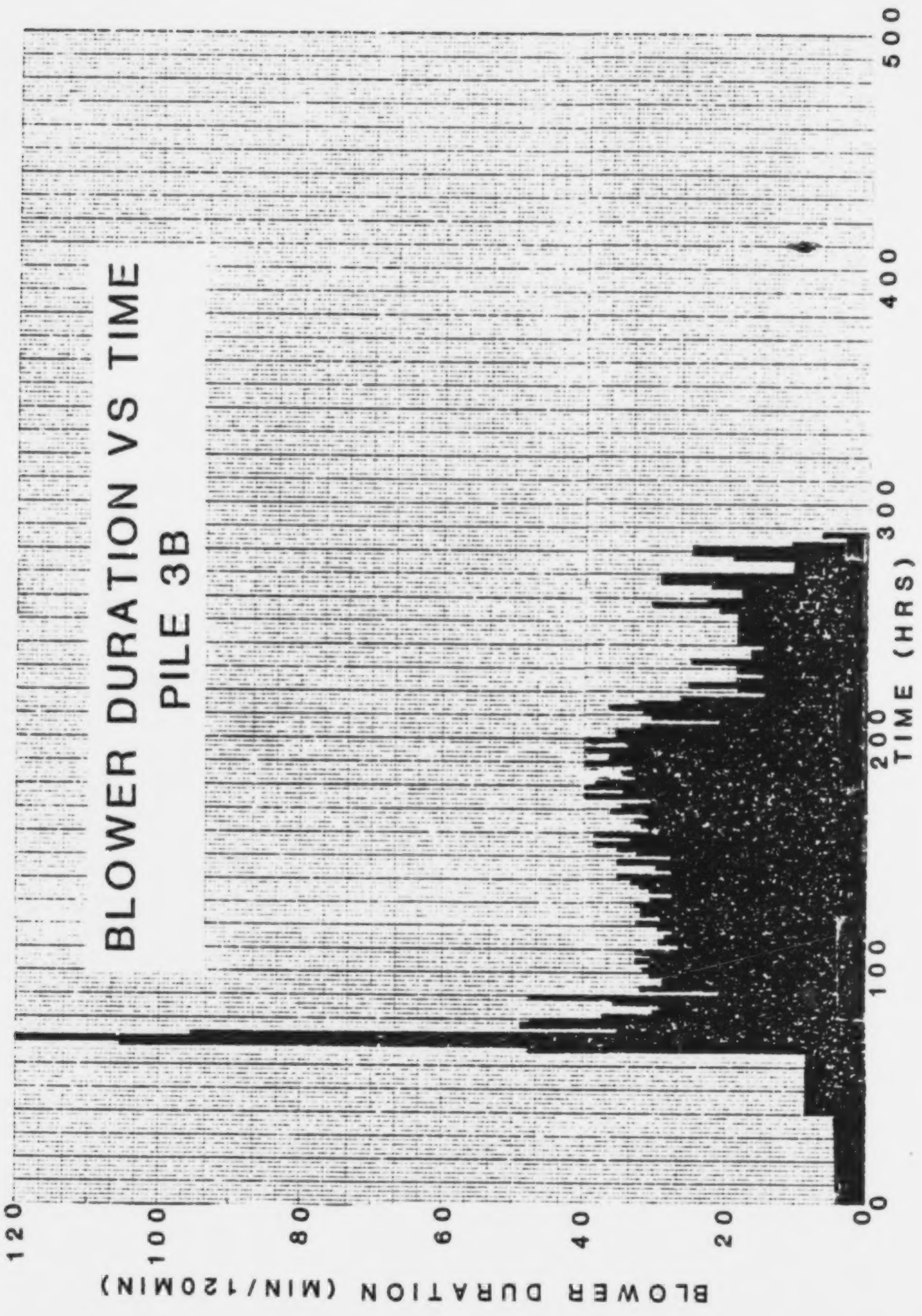

BLOWER DURATION VS TIME
PILE 3B
BLOWER DURATION (MIN/120MIN)
120
100
80
60
40
20
0
TIME (HRS)
0
100
200
300
400
500

FIG 46

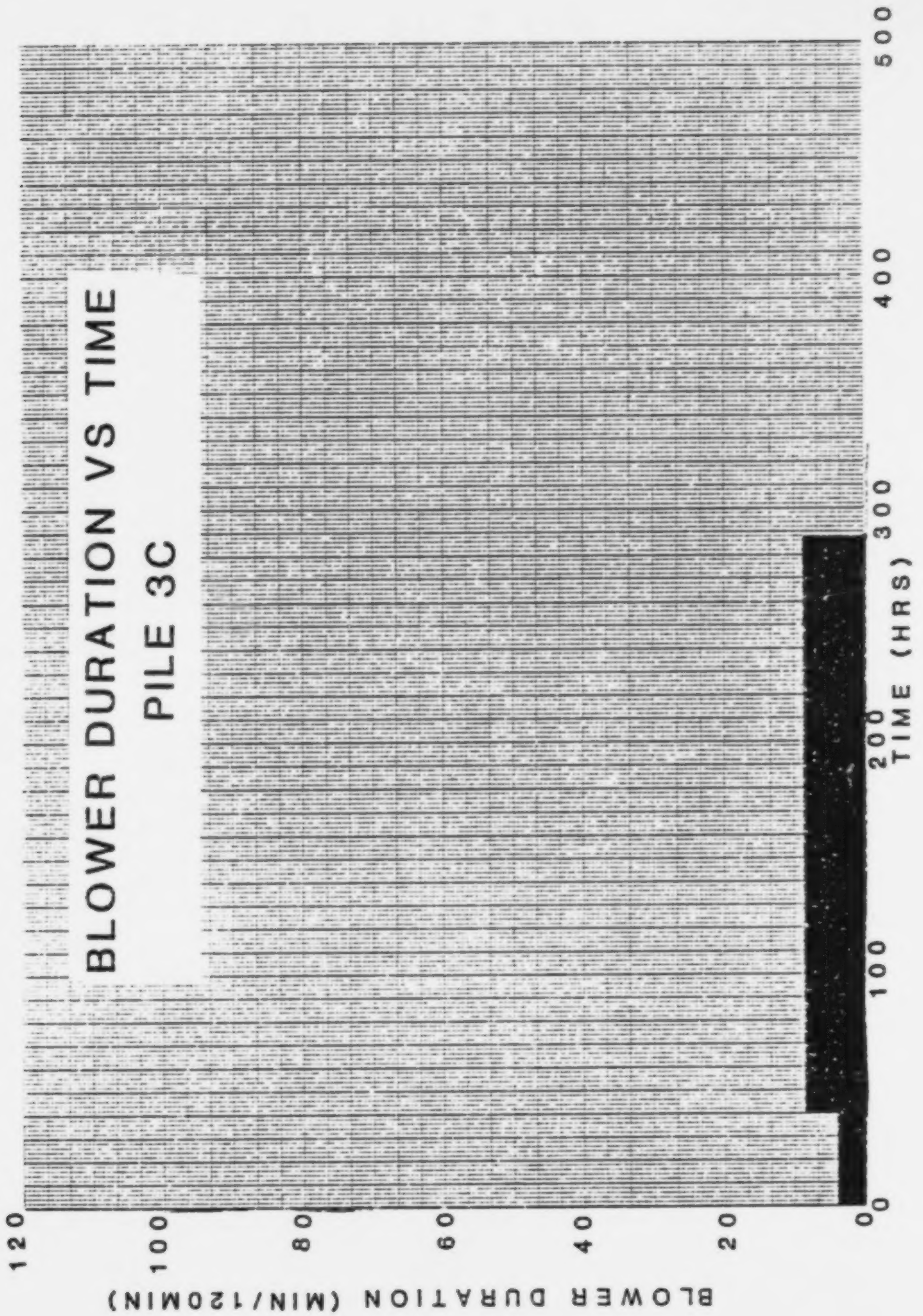

BLOWER DURATION VS TIME
PILE 3C
BLOWER DURATION (MIN/120MIN)
0
20
40
60
80
100
120
TIME (HRS)
0
100
200
300
400
500

FIG 47

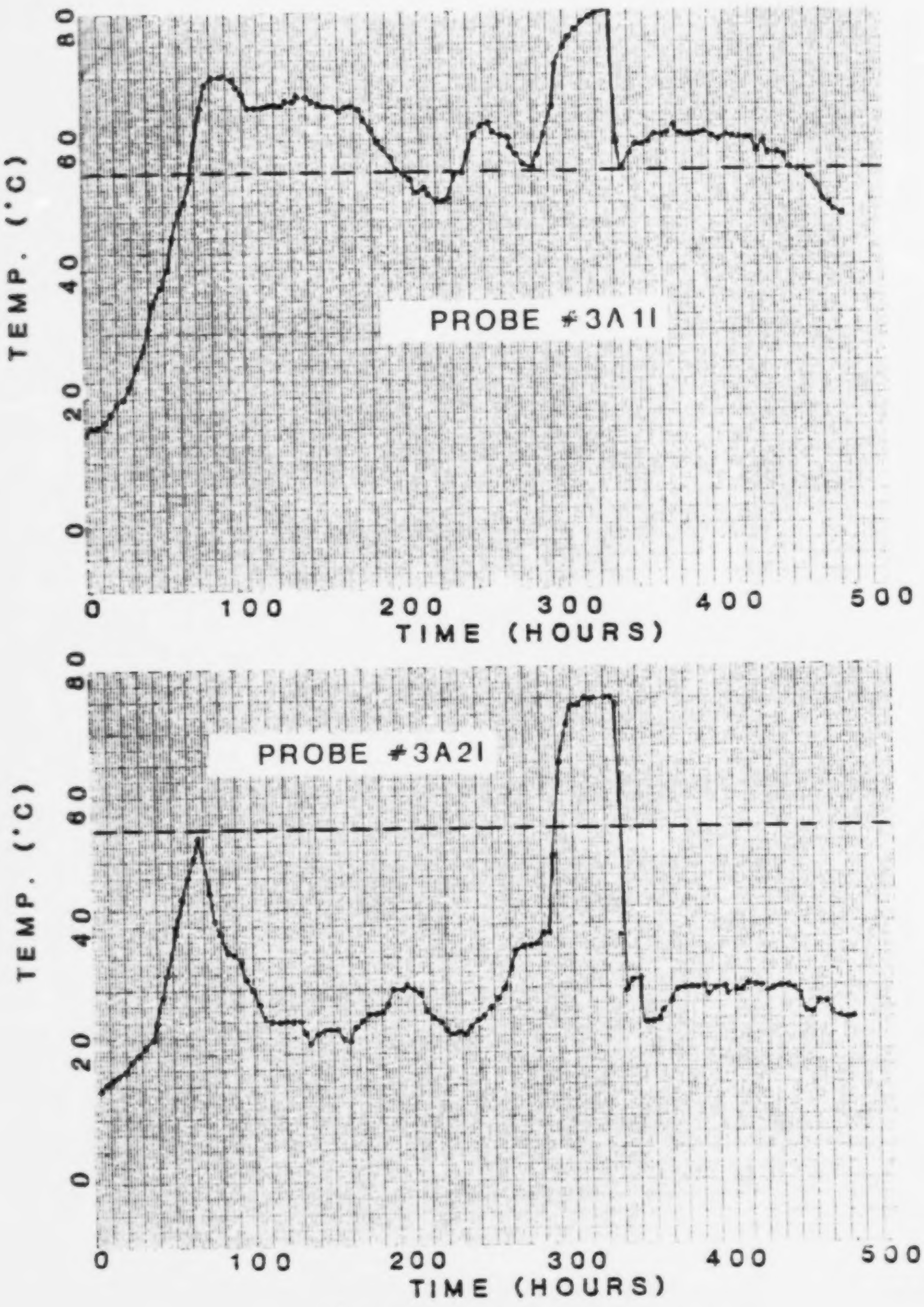

TEMP. VS TIME:
PILE 3A, PROBE #1I,2I

FIGURE 48

TEMP. VS TIME: PILE 3A, PROBE # 31,41

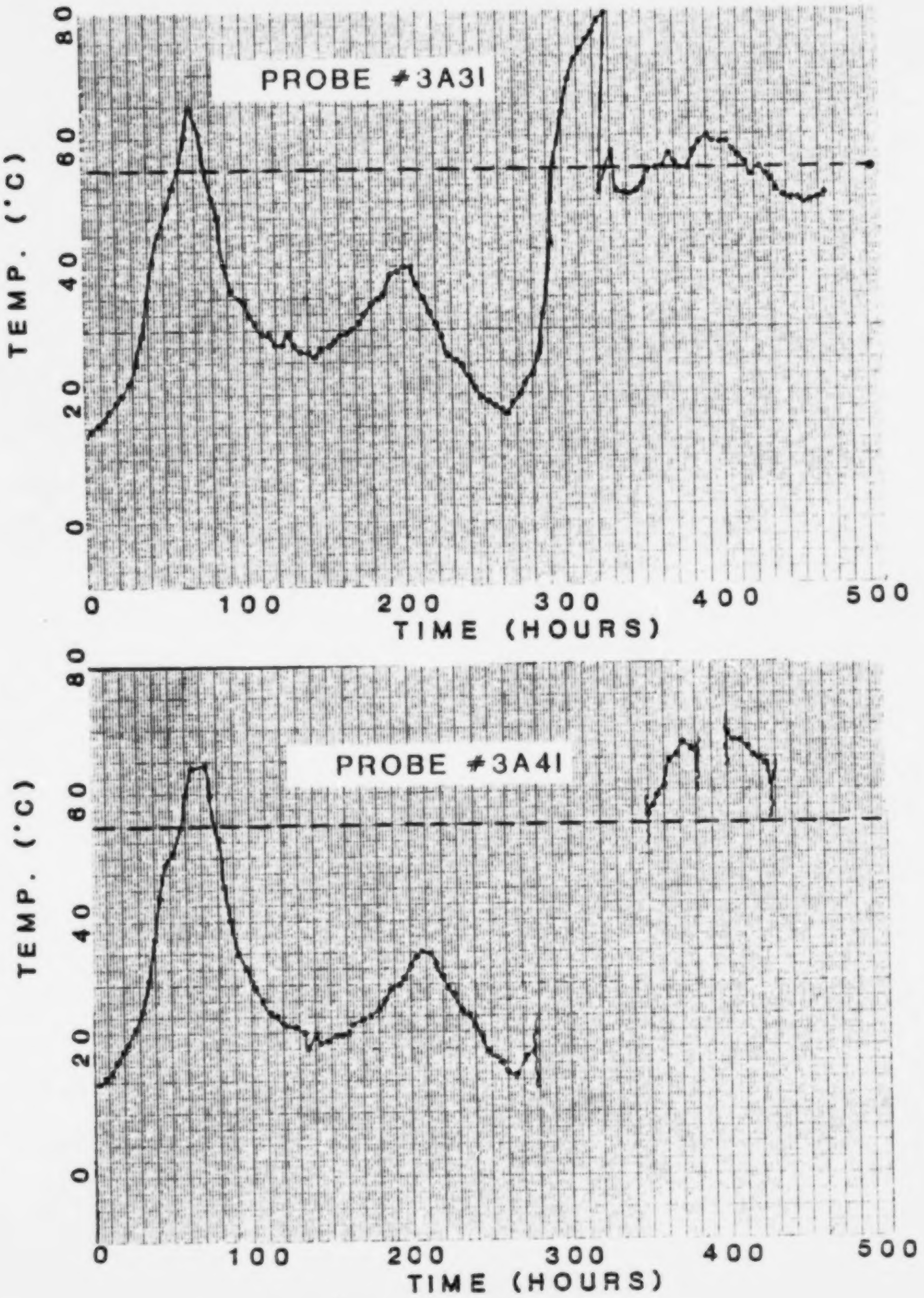


FIGURE 49

TEMP. VS TIME: PILE 3A, PROBE #51

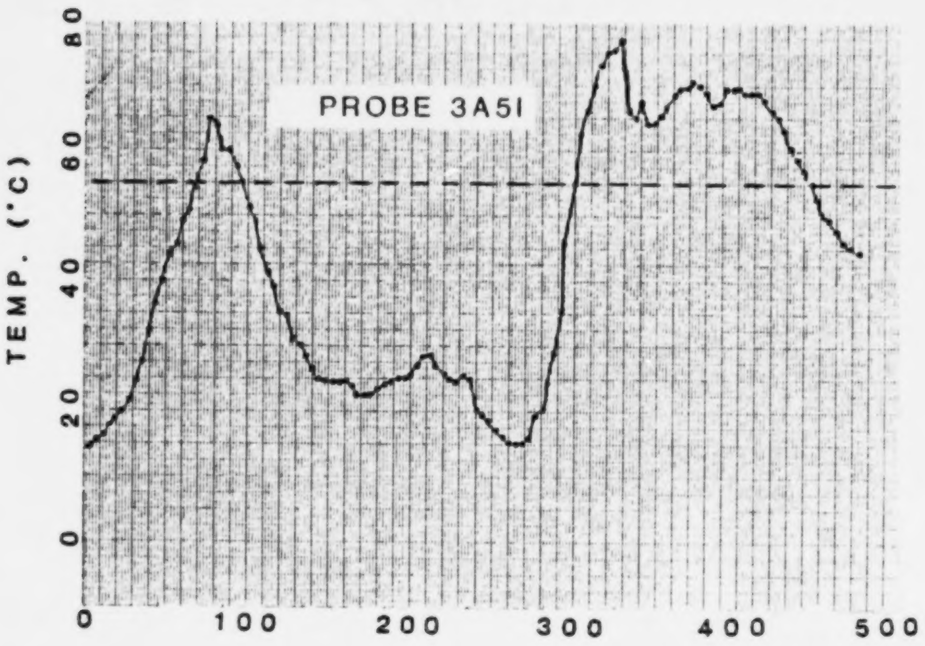


FIGURE 50

TEMP. VS TIME:
PILE 3B, PROBE #1I,2I

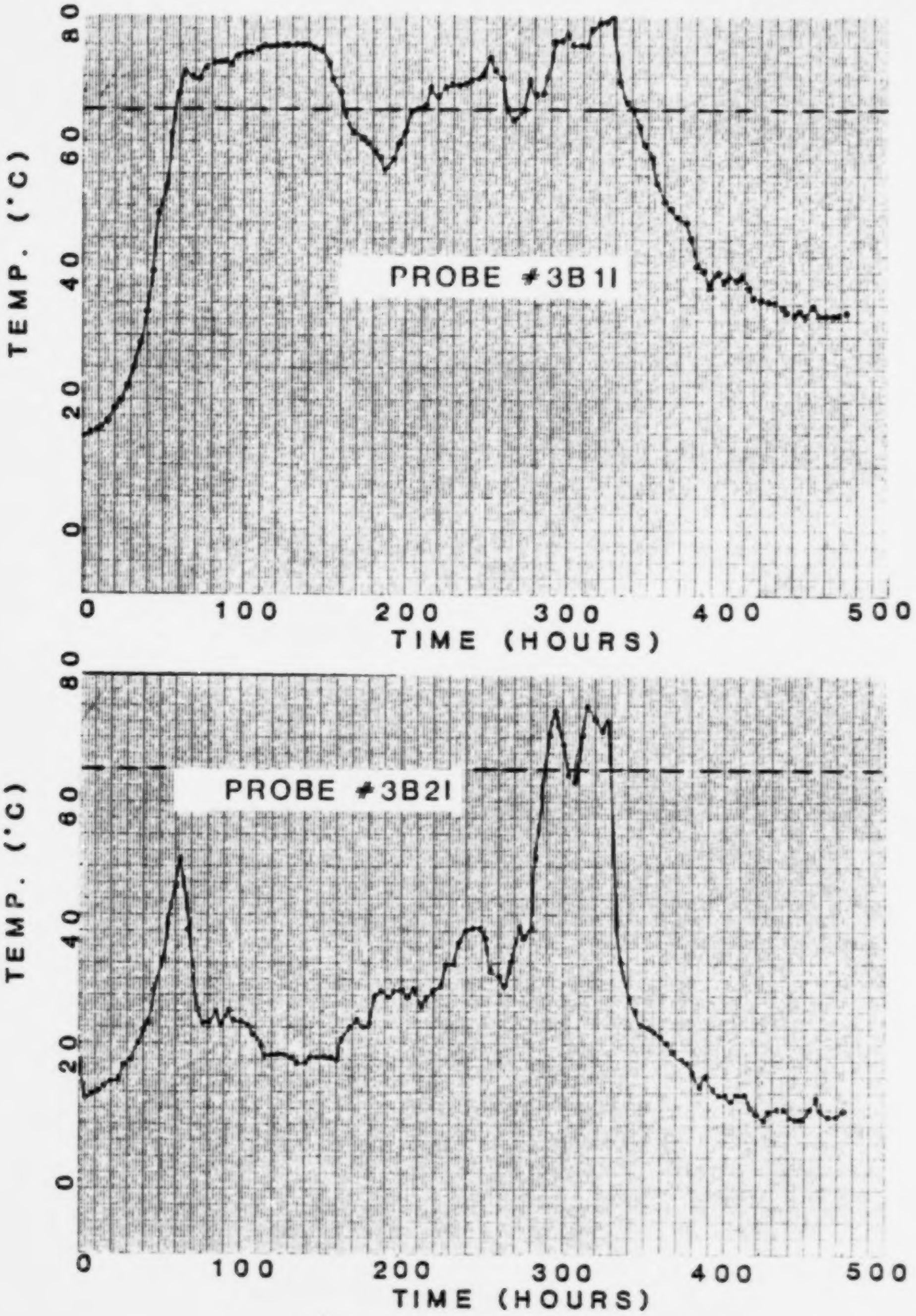


FIGURE 51

TEMP. VS TIME:
PILE 3B, PROBE #31,51

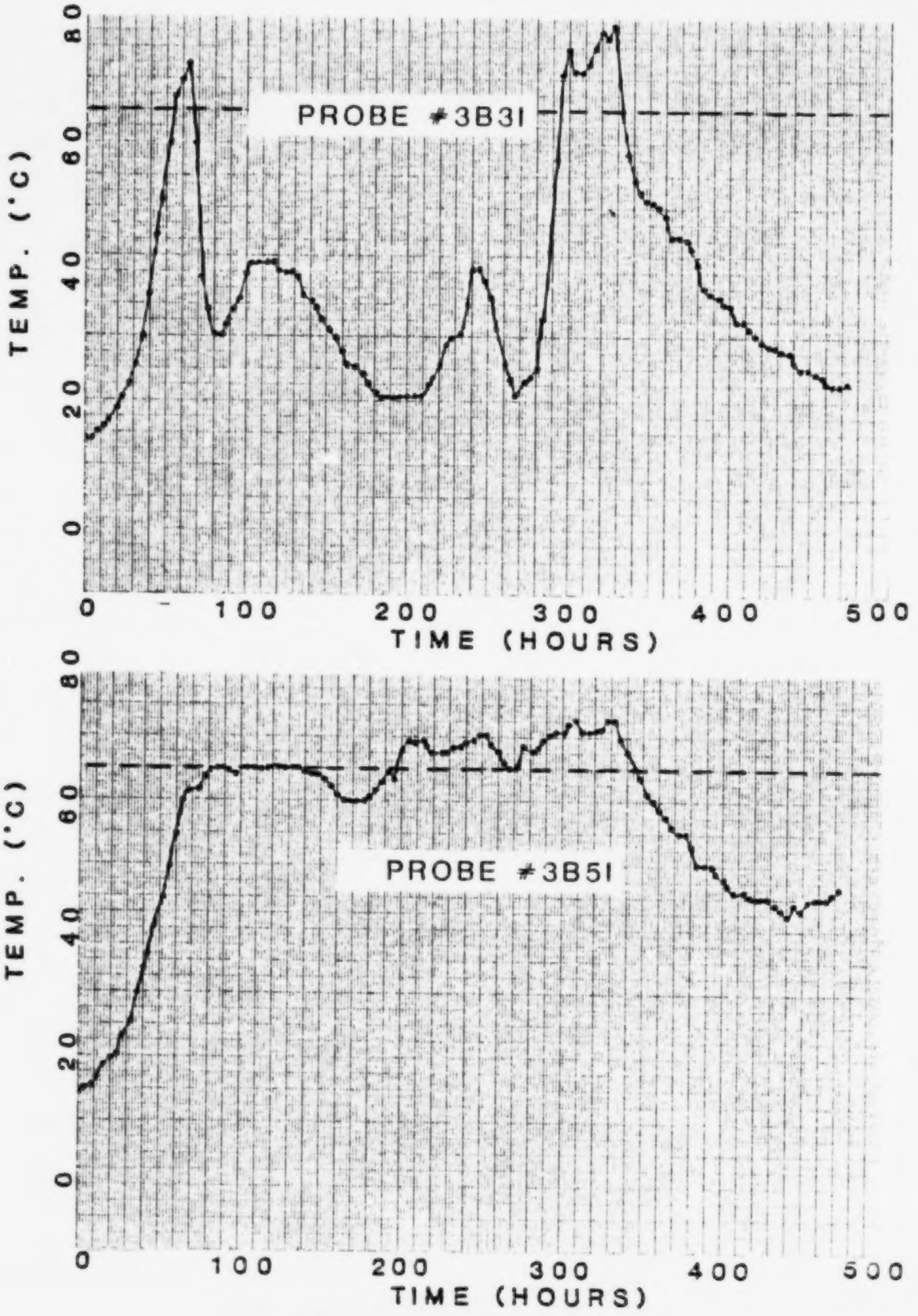


FIGURE 52

TEMP. VS TIME: PILE 3C, PROBE #1I,2I

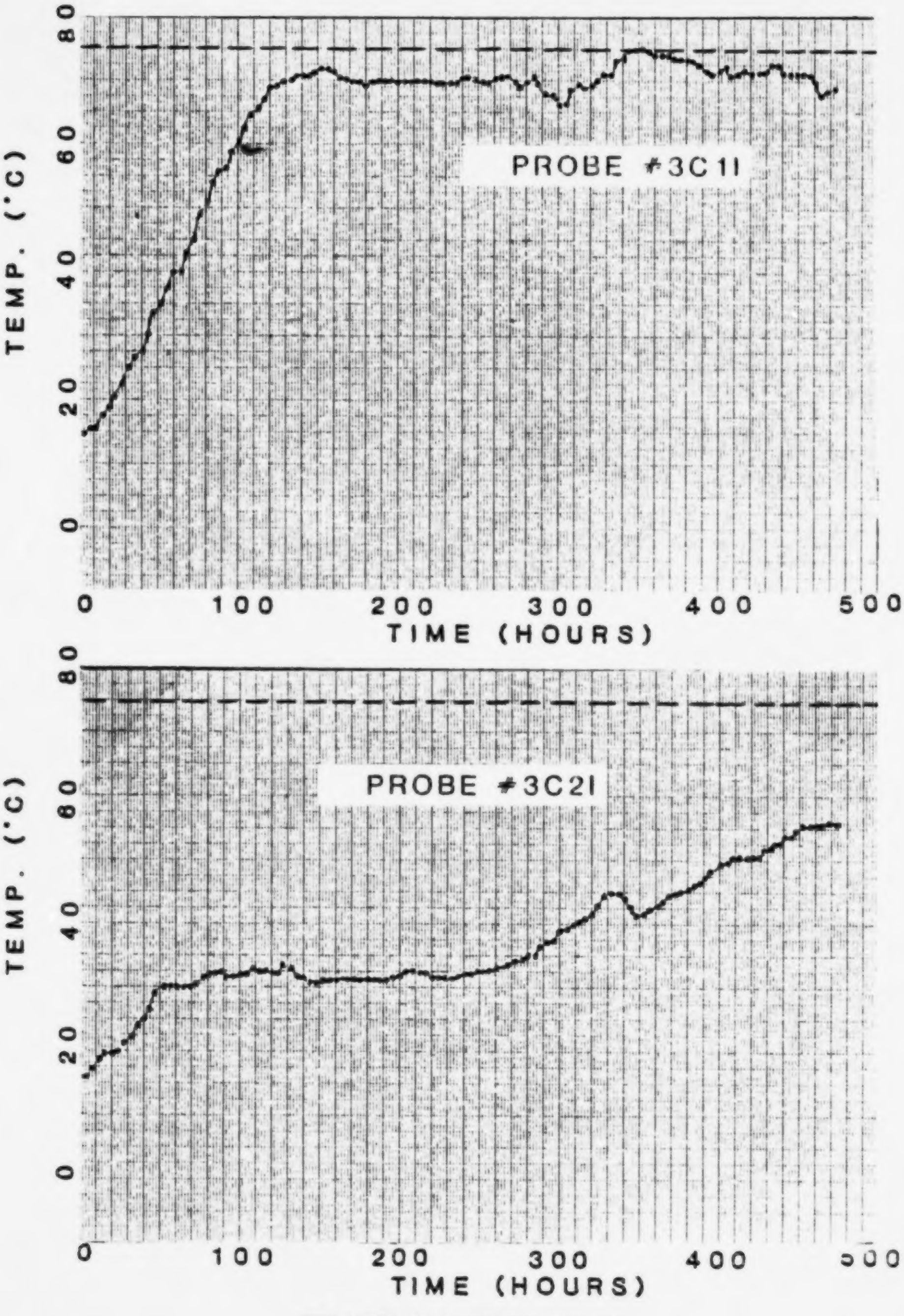


FIGURE 53

TEMP. VS TIME:
PILE 3C, PROBE #31,41

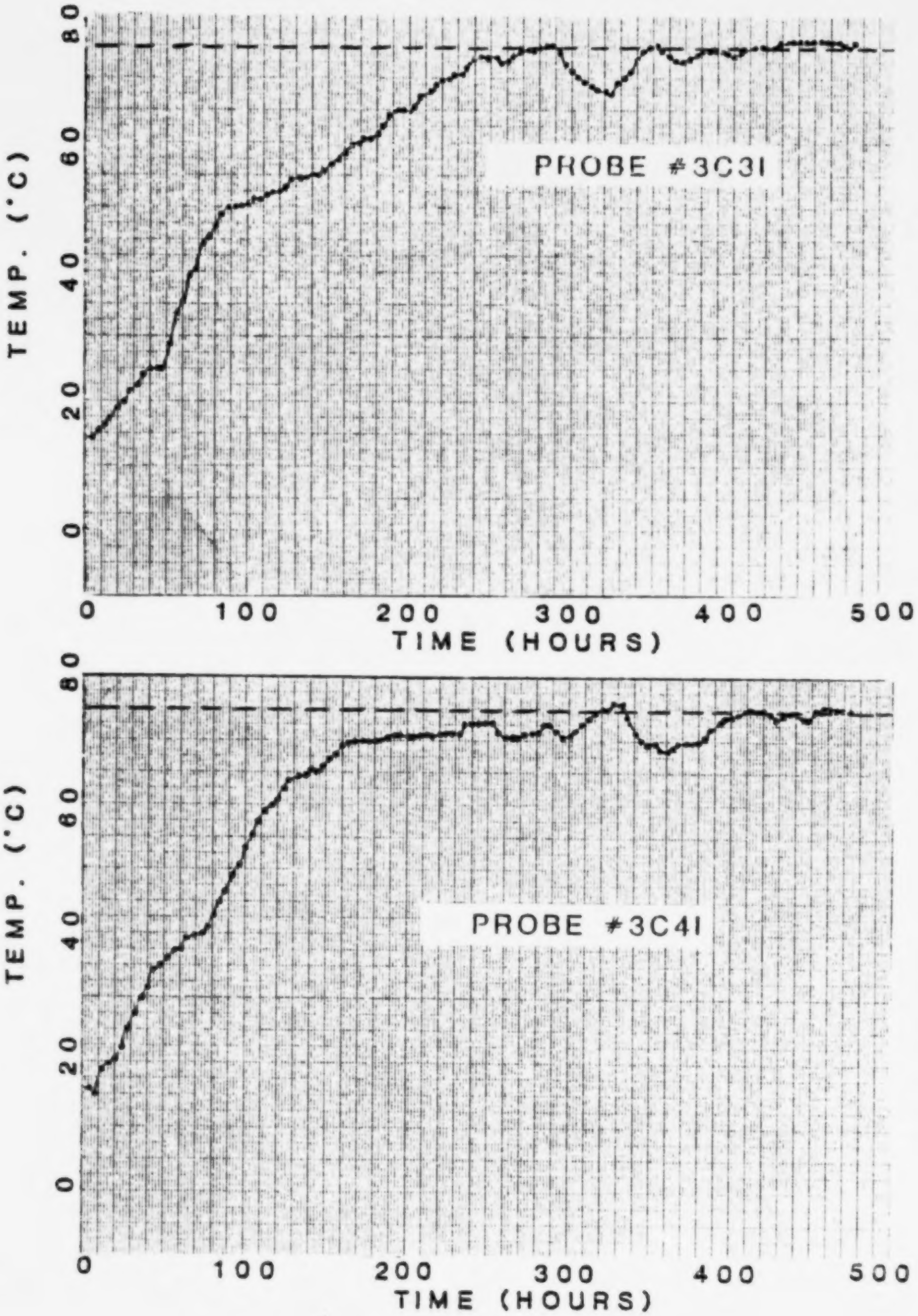


FIGURE 54

TEMP. VS TIME:
PILE 3C, PROBE #51

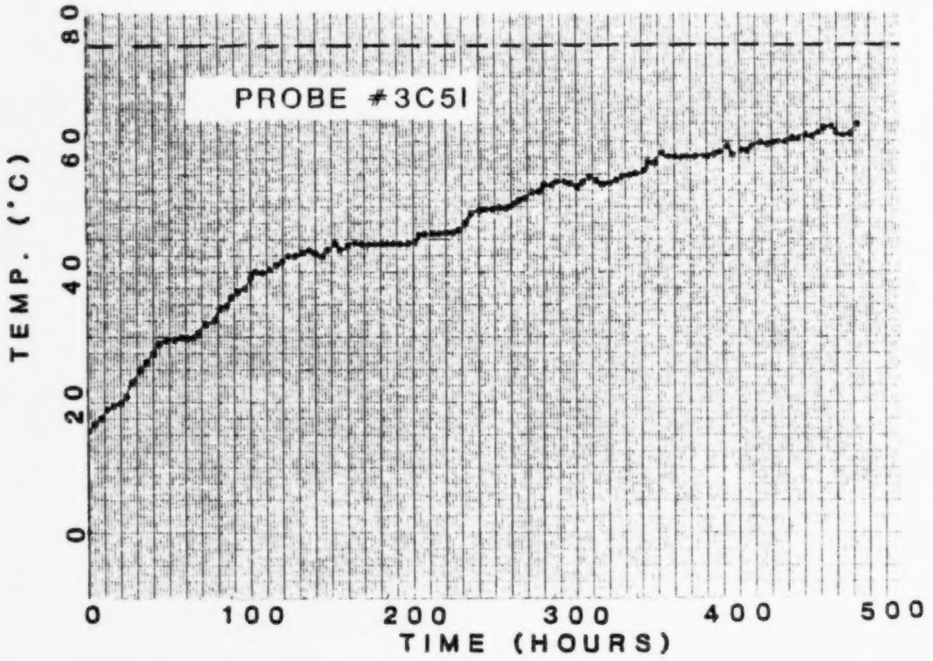


FIGURE 55

TEMP. VS TIME:
PILE3A,PROBE #1S,2S

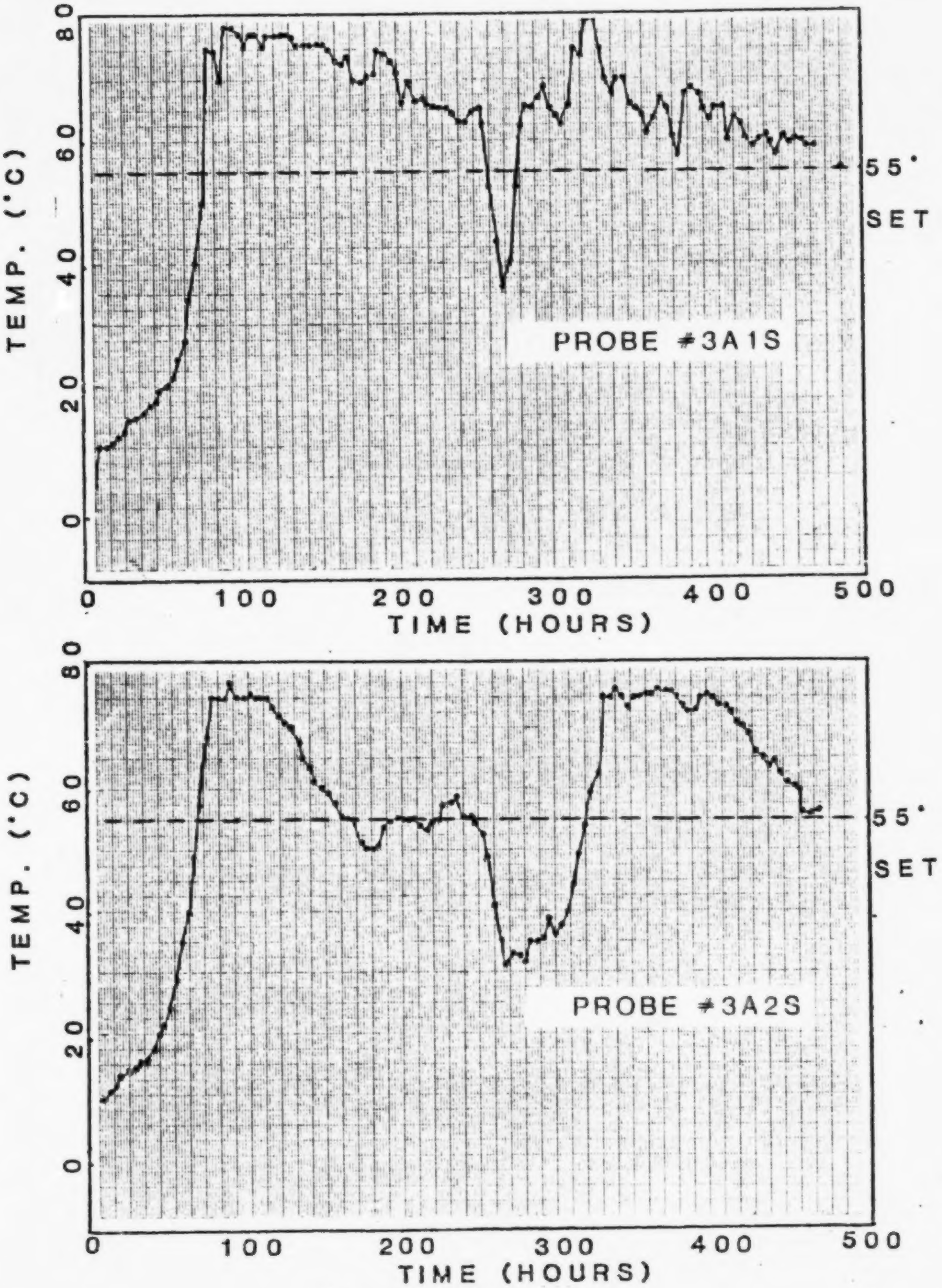


FIGURE 56

TEMP. VS TIME:
PILE3A,PROBE # 3S,4S

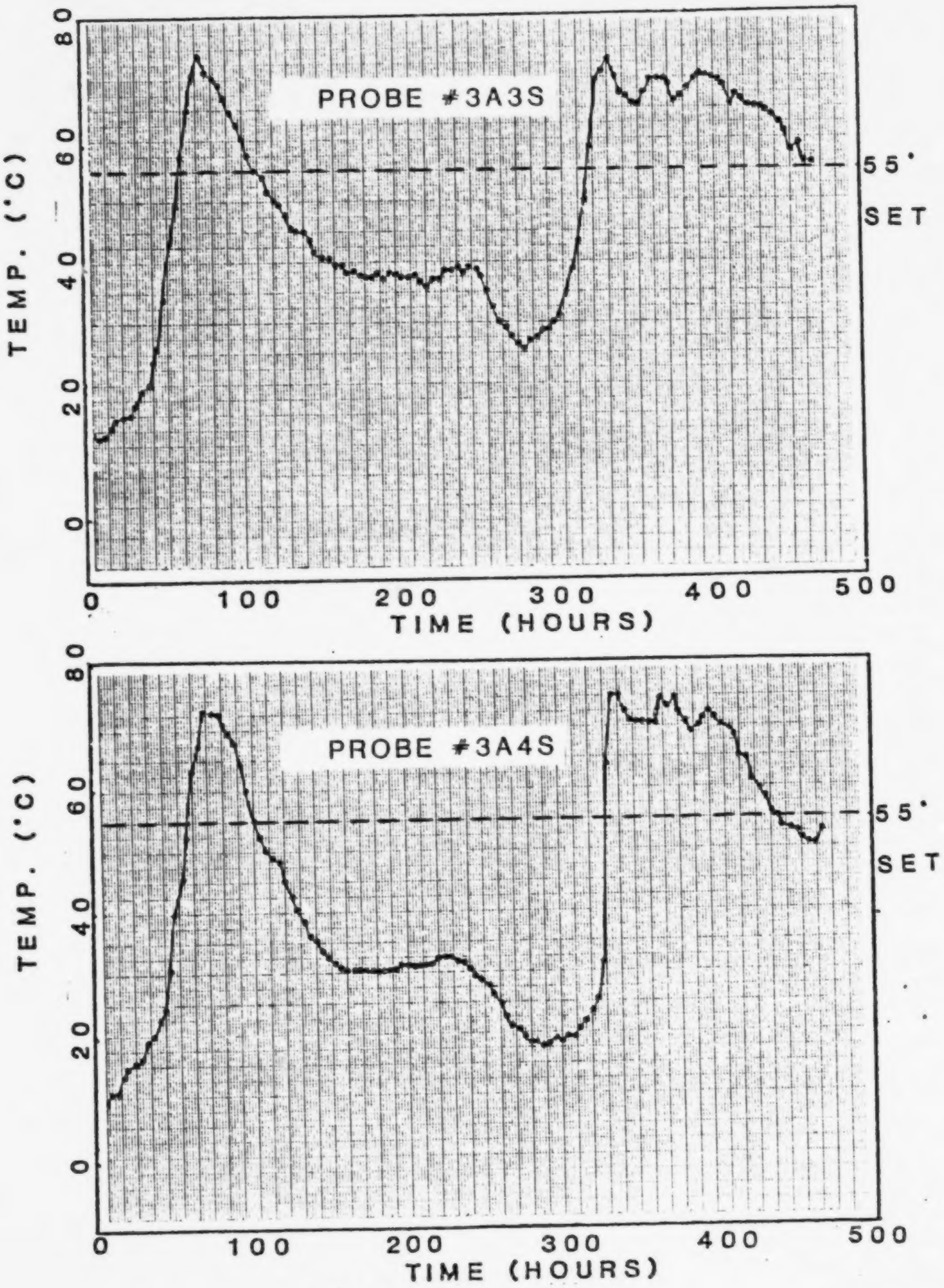


FIGURE 57

TEMP. VS TIME:
PILE3A,PROBE #6S

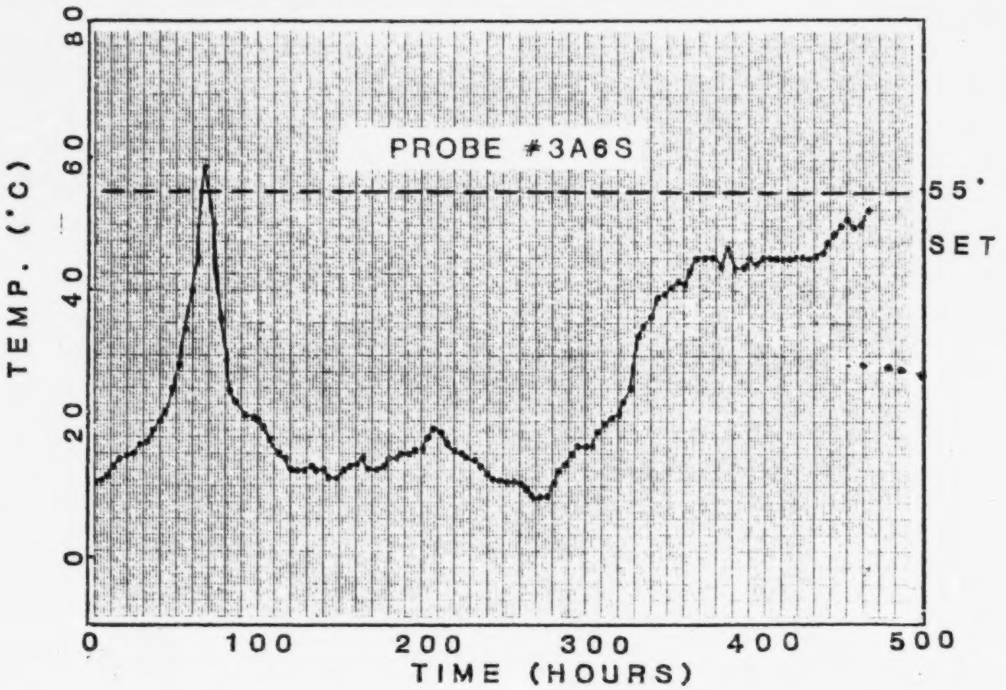


FIGURE 58

TEMP. VS TIME: PILE3B,PROBE #1S,2S

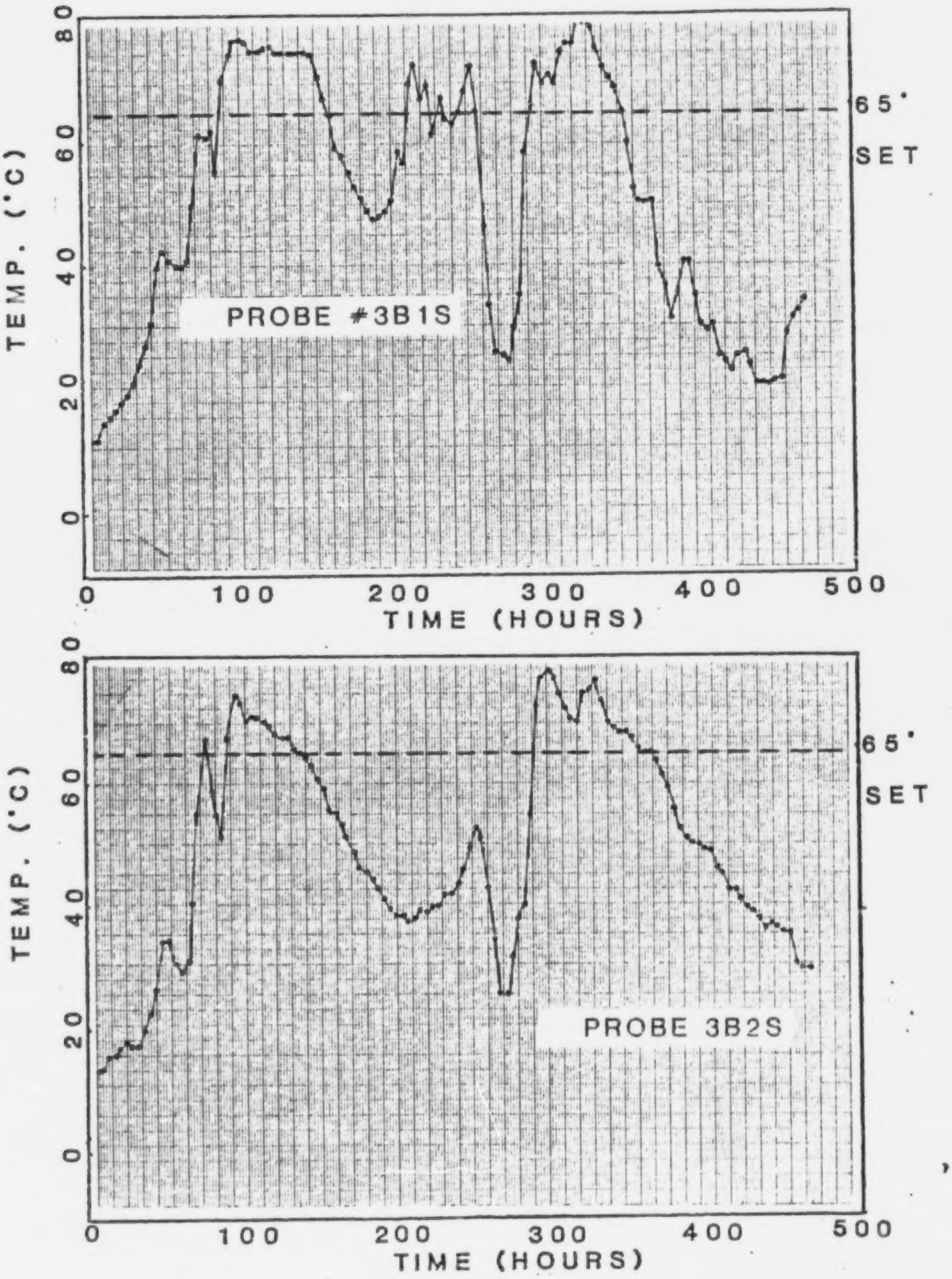


FIGURE 59

TEMP. VS TIME: PILE3B,PROBE #3S,4S

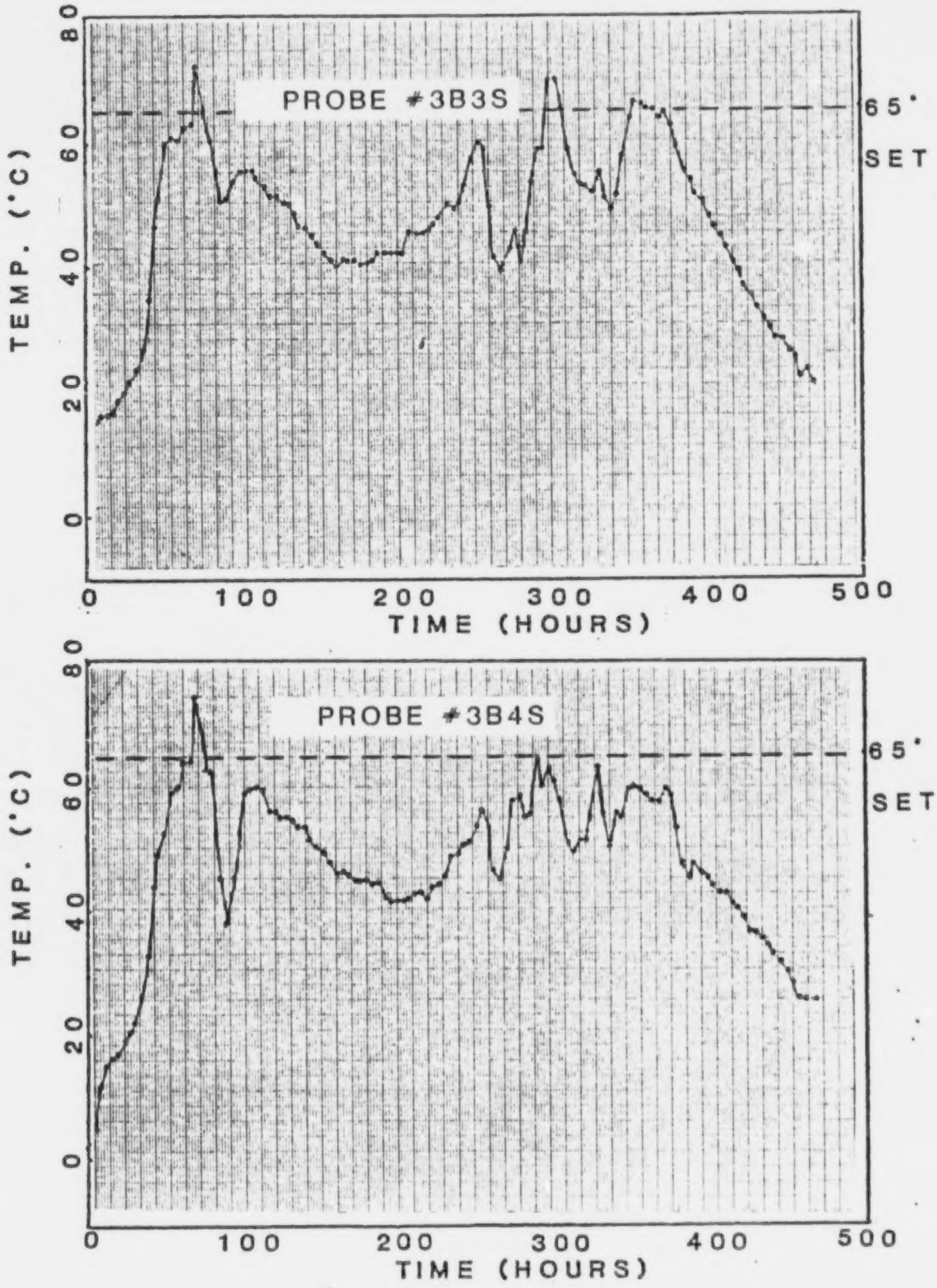


FIGURE 60

TEMP. VS TIME: PILE3B,PROBE #6S

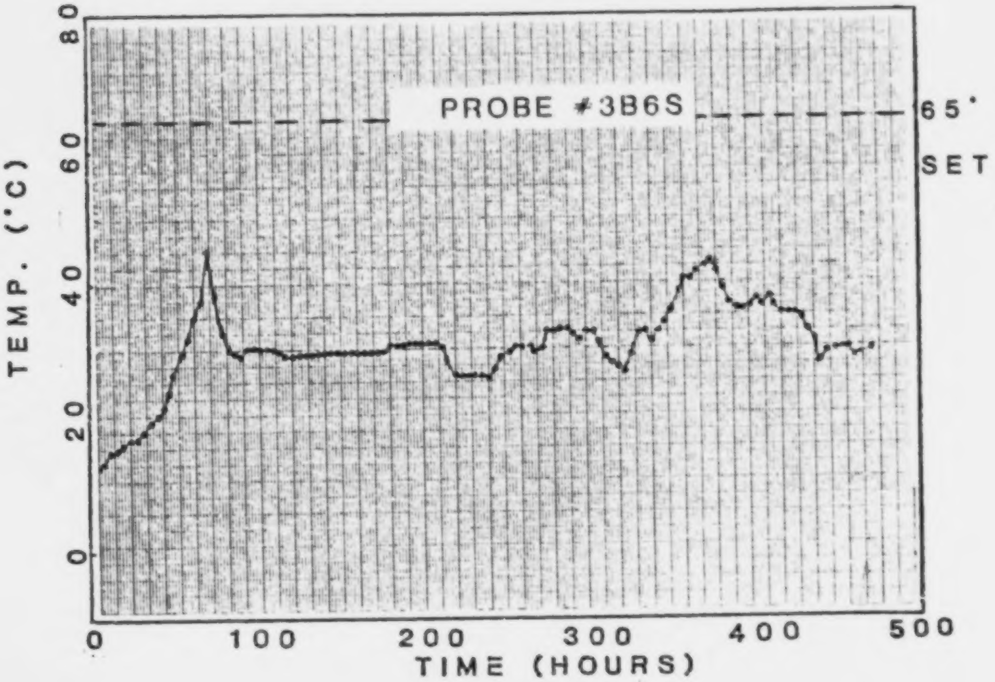


FIGURE 61

TEMP. VS TIME:
PILE3C,PROBE #1S,2S

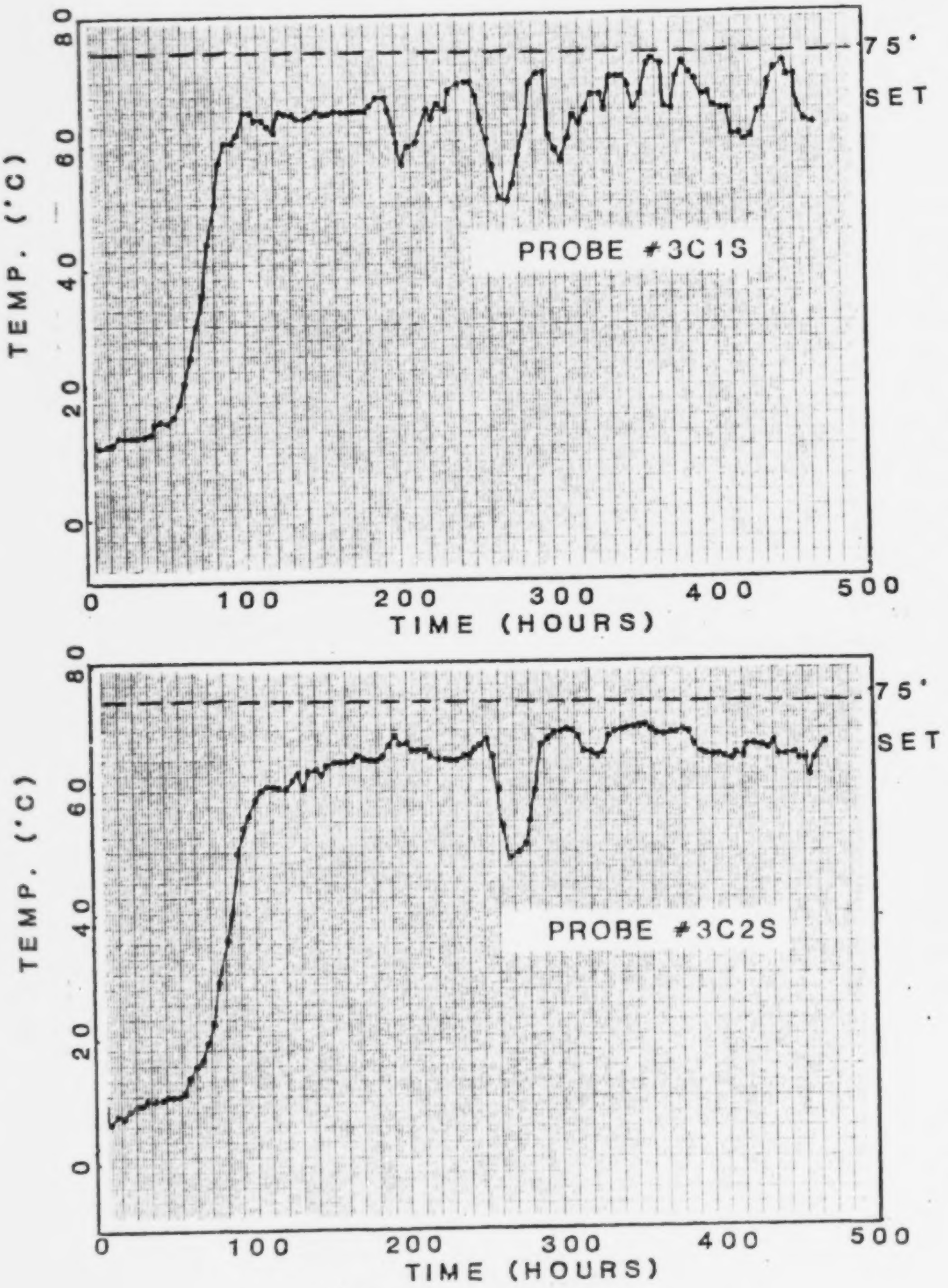


FIGURE 62

TEMP. VS TIME: PILE3C,PROBE #3S,4S

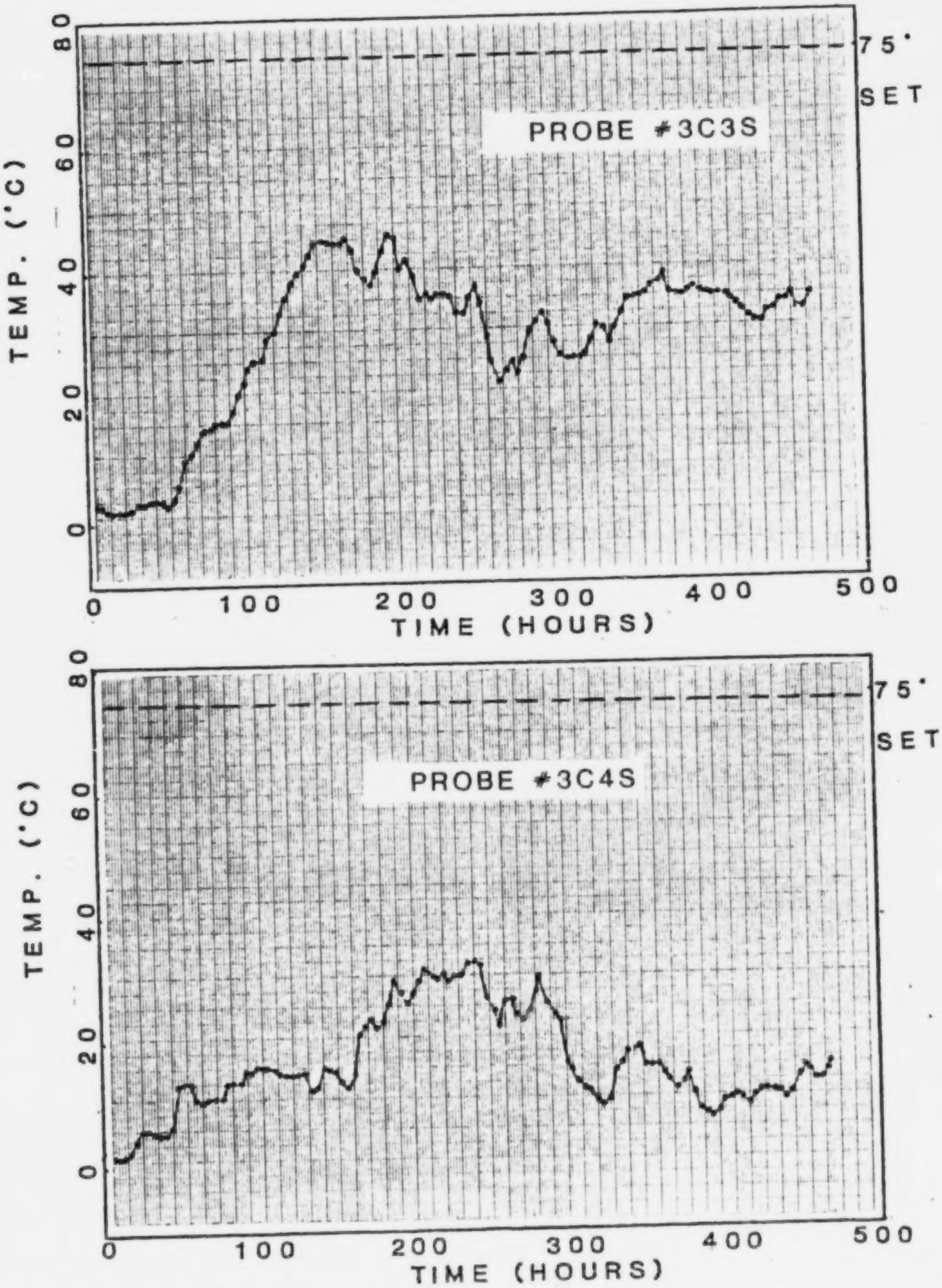


FIGURE 63

TEMP. VS TIME:
PILE3C,PROBE #5S,6S

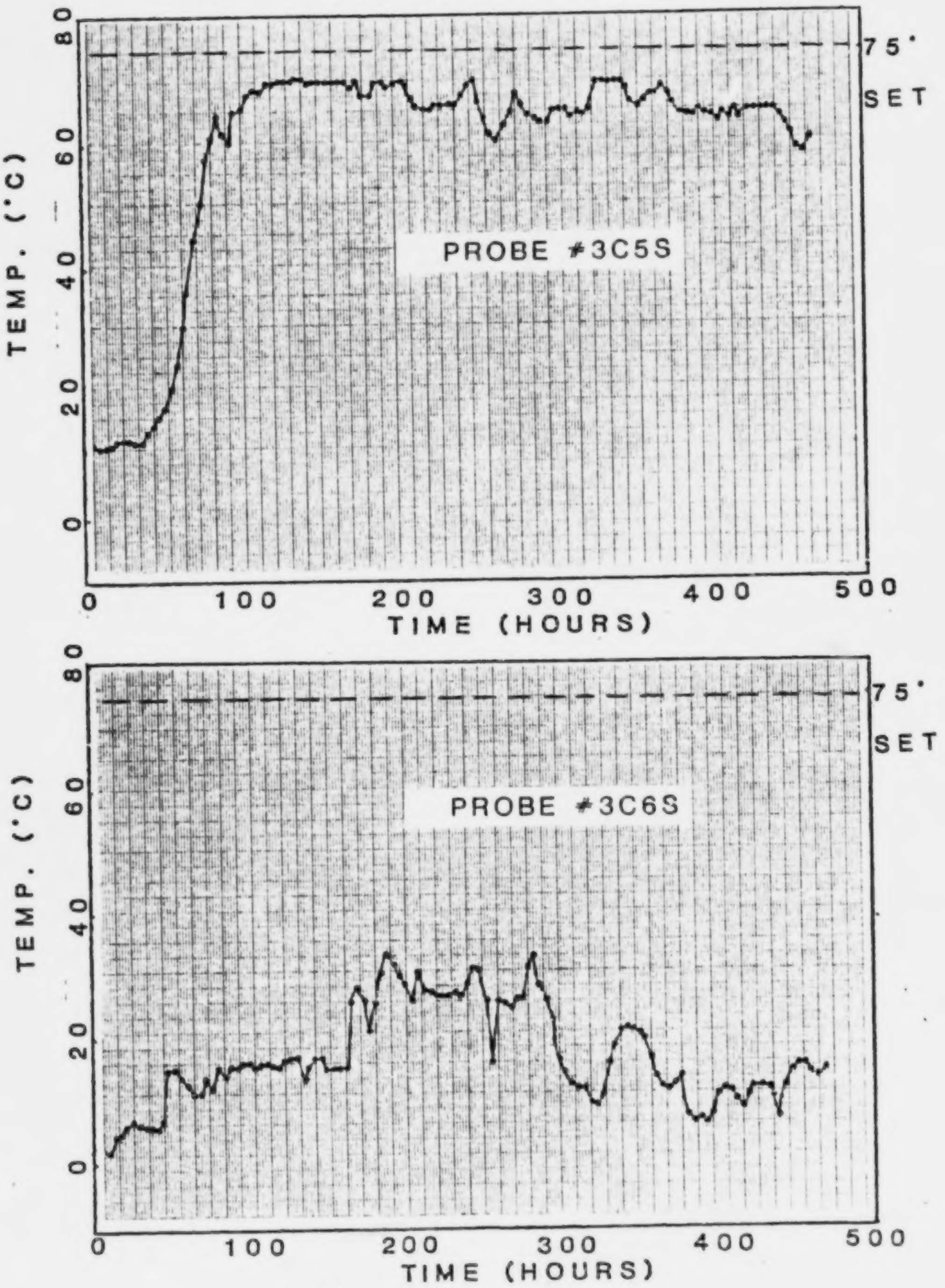


FIGURE 64

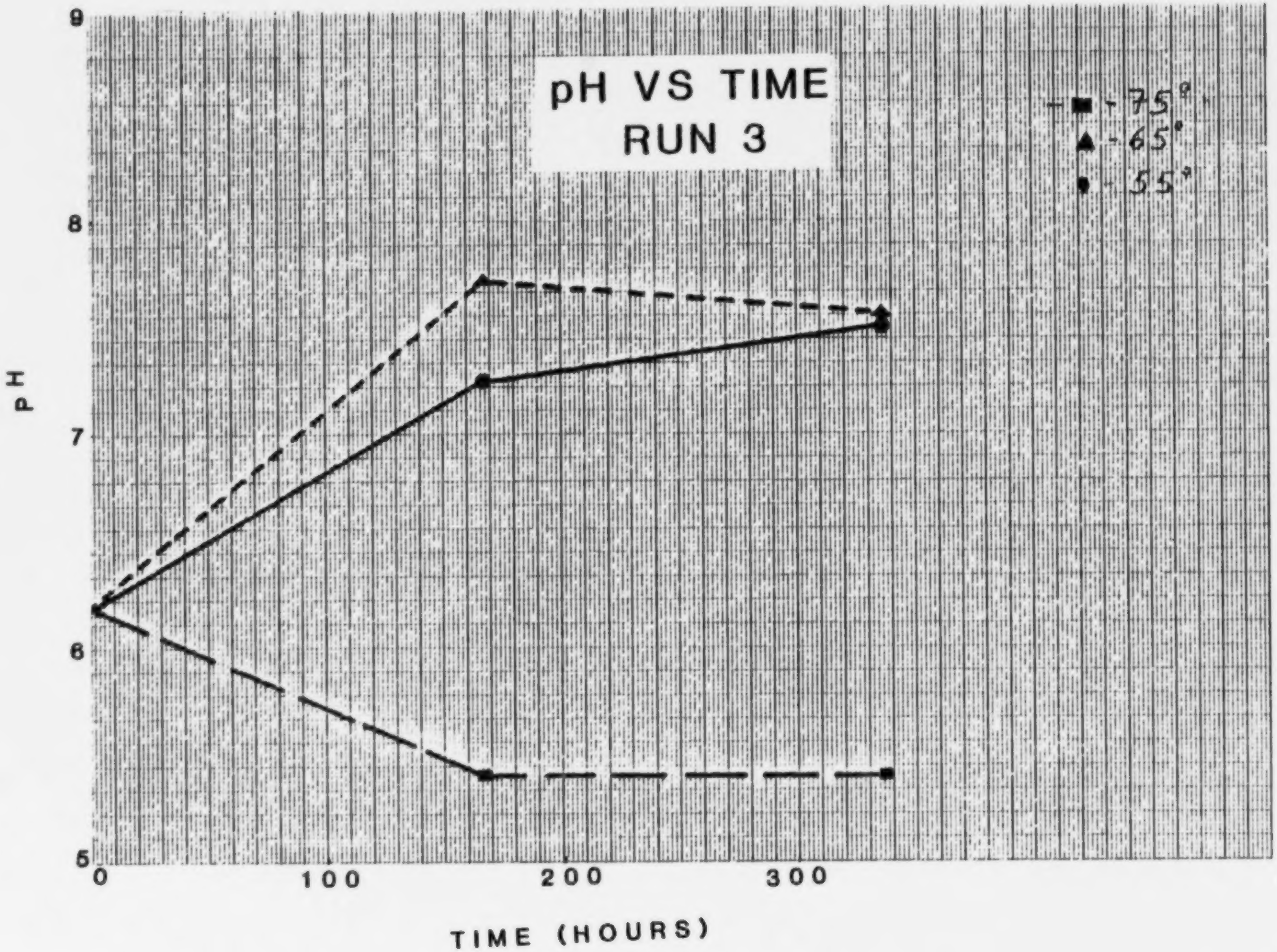


FIG 65

% CO2 VS TIME-PILE 3A,3B

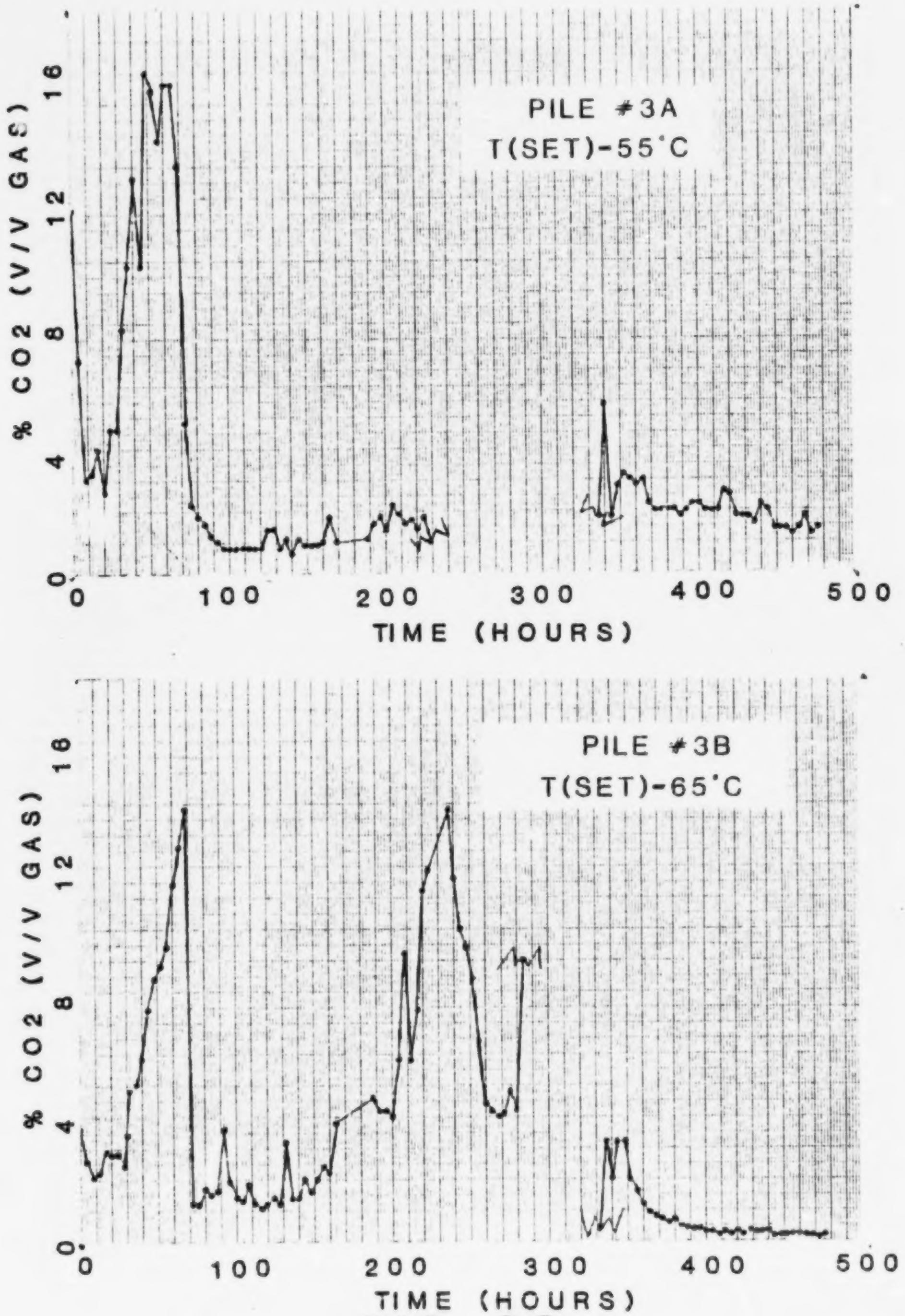


FIG 66

% CO2 VS TIME–PILE 3C

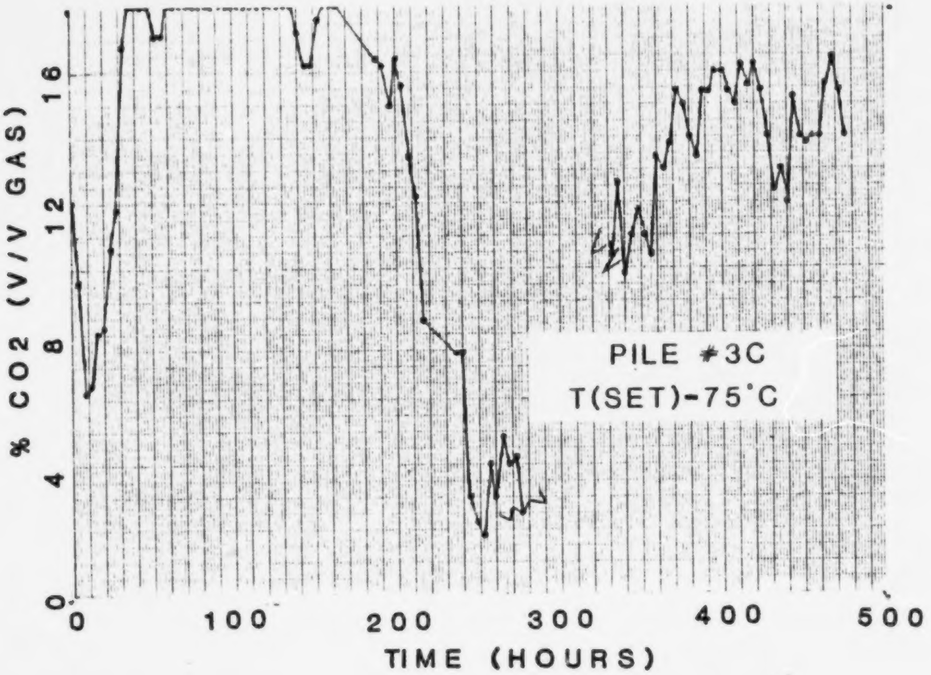


FIG 67

MOISTURE CONTENT VS TIME RUN 3

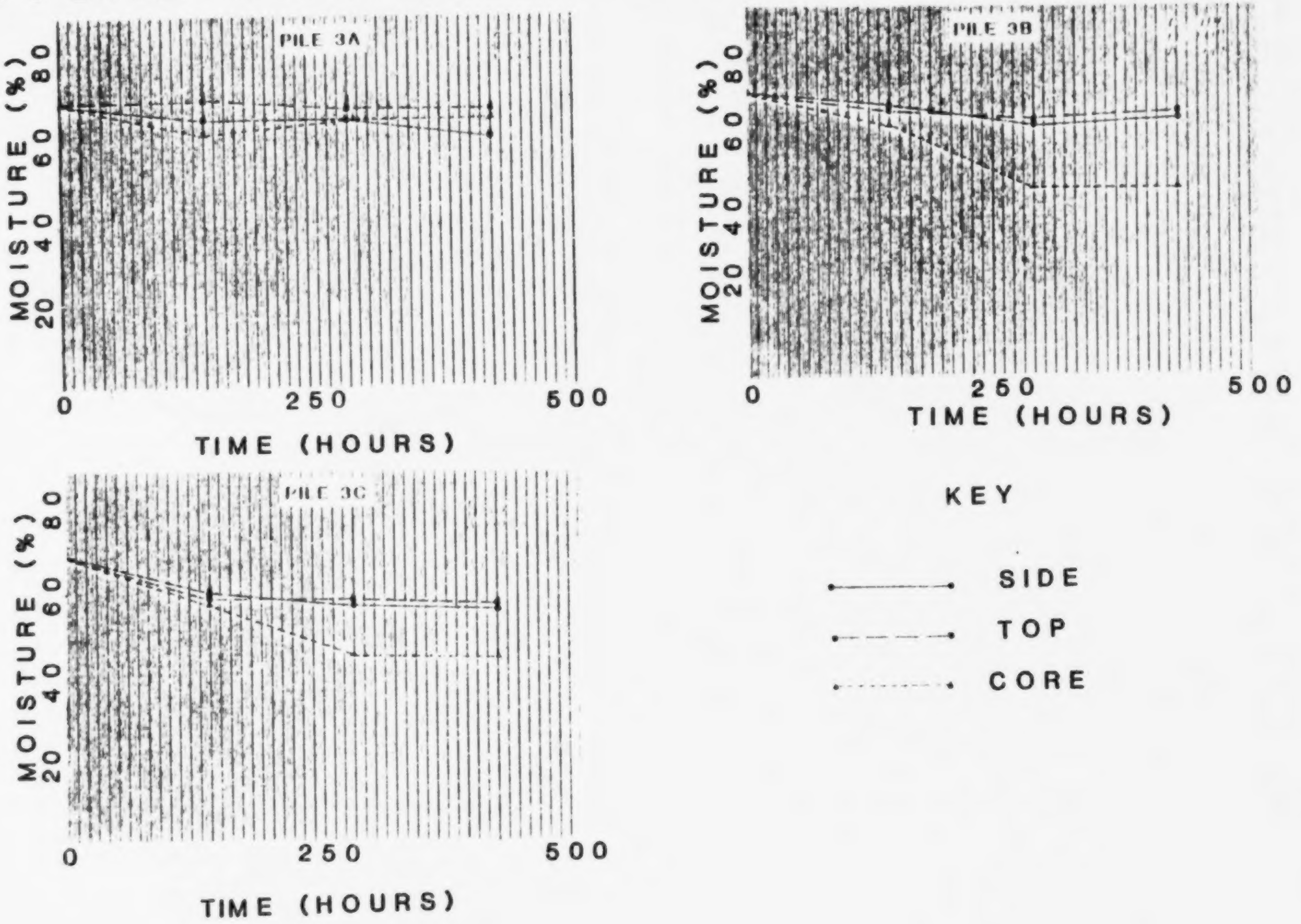


FIG 68

RUN #4 PROBE LOCATION KEY

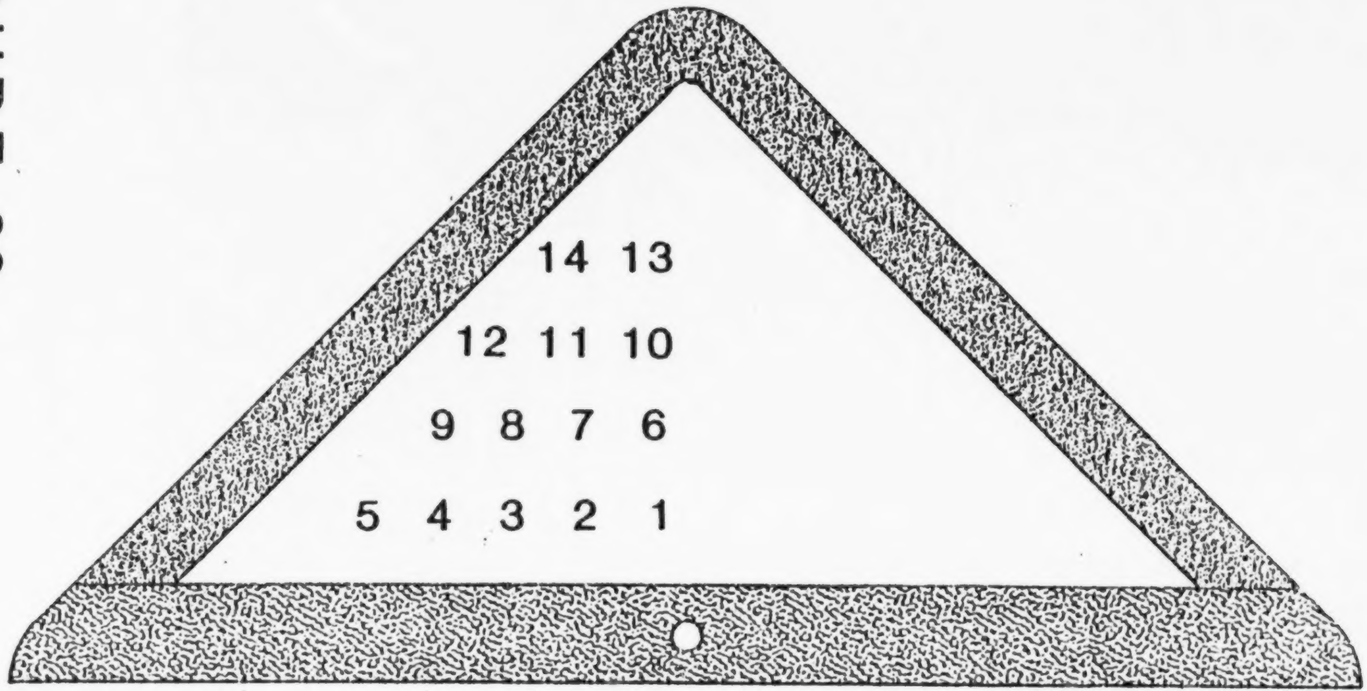

14 13
12 11 10
9 8 7 6
5 4 3 2 1

FIGURE 69

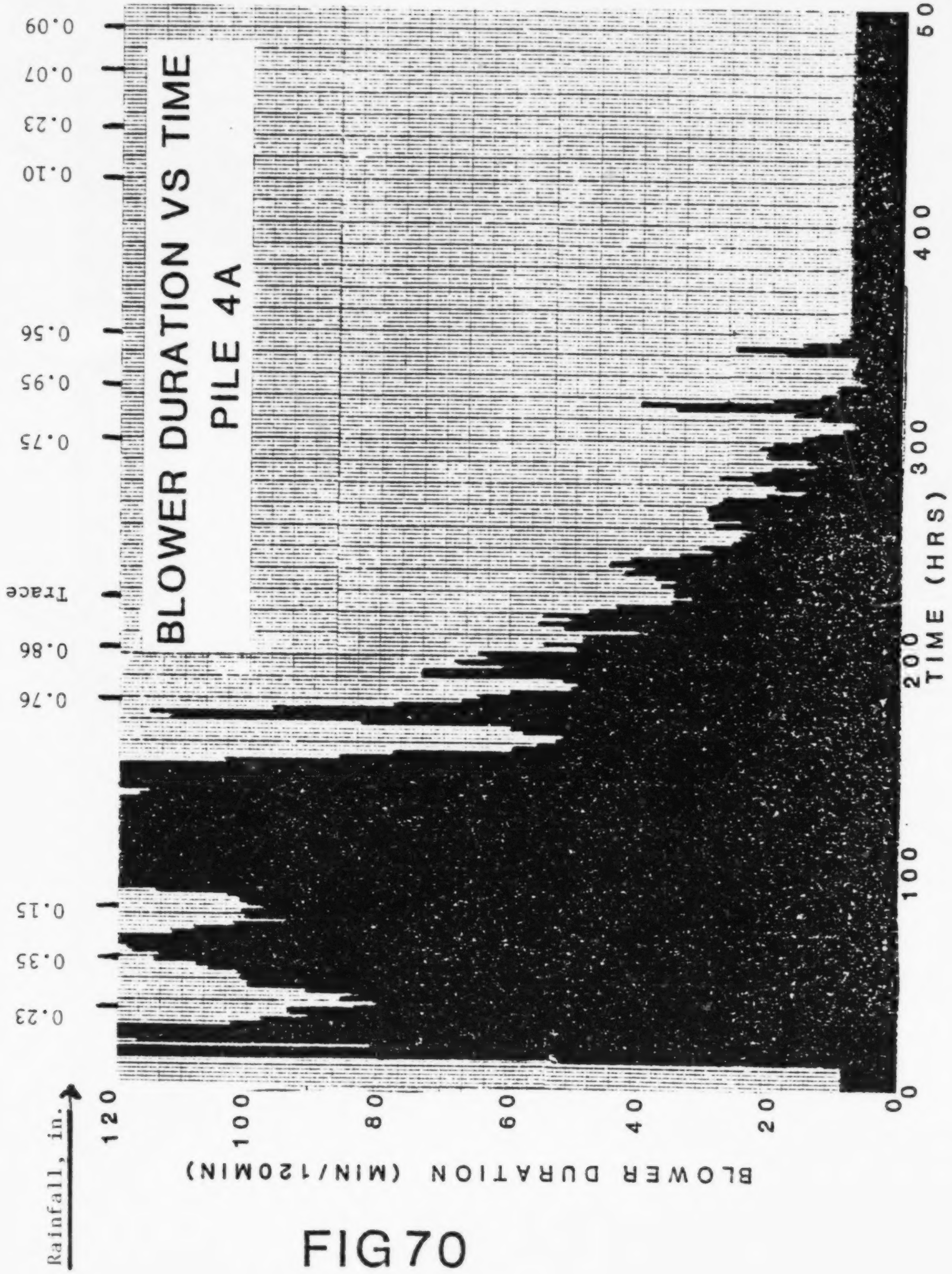

BLOWER DURATION VS TIME
PILE 4A
BLOWER DURATION (MIN/120MIN)
120
100
80
60
40
20
0
TIME (HRS)
0
100
200
300
400
500
Rainfall, in.
0.23
0.35
0.15
0.76
0.86
Trace
0.75
0.95
0.56
0.10
0.23
0.07
0.09

FIG 70

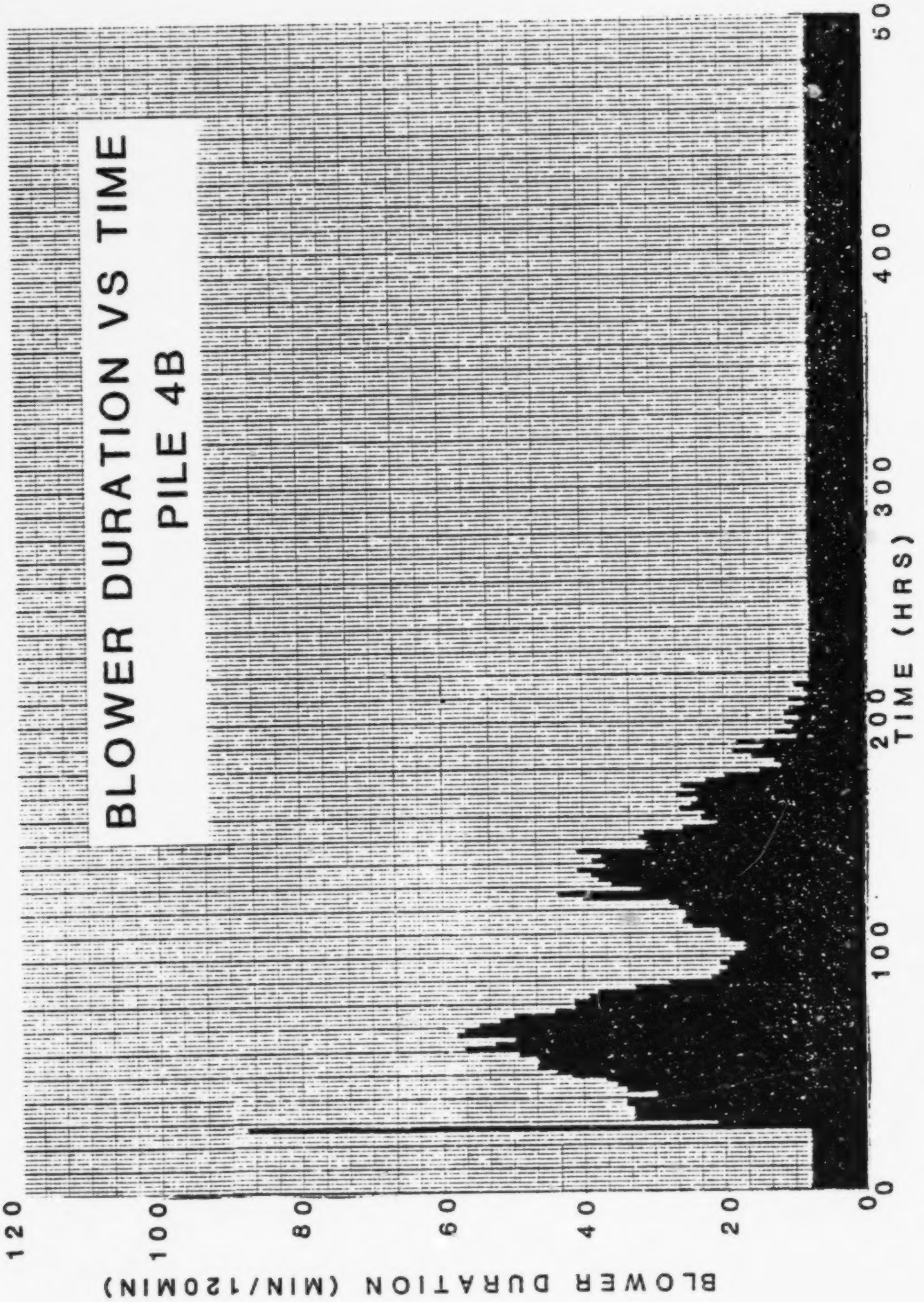

BLOWER DURATION VS TIME
PILE 4B
BLOWER DURATION (MIN/120MIN)
120
100
80
60
40
20
0
TIME (HRS)
0
100
200
300
400
500

FIG 71

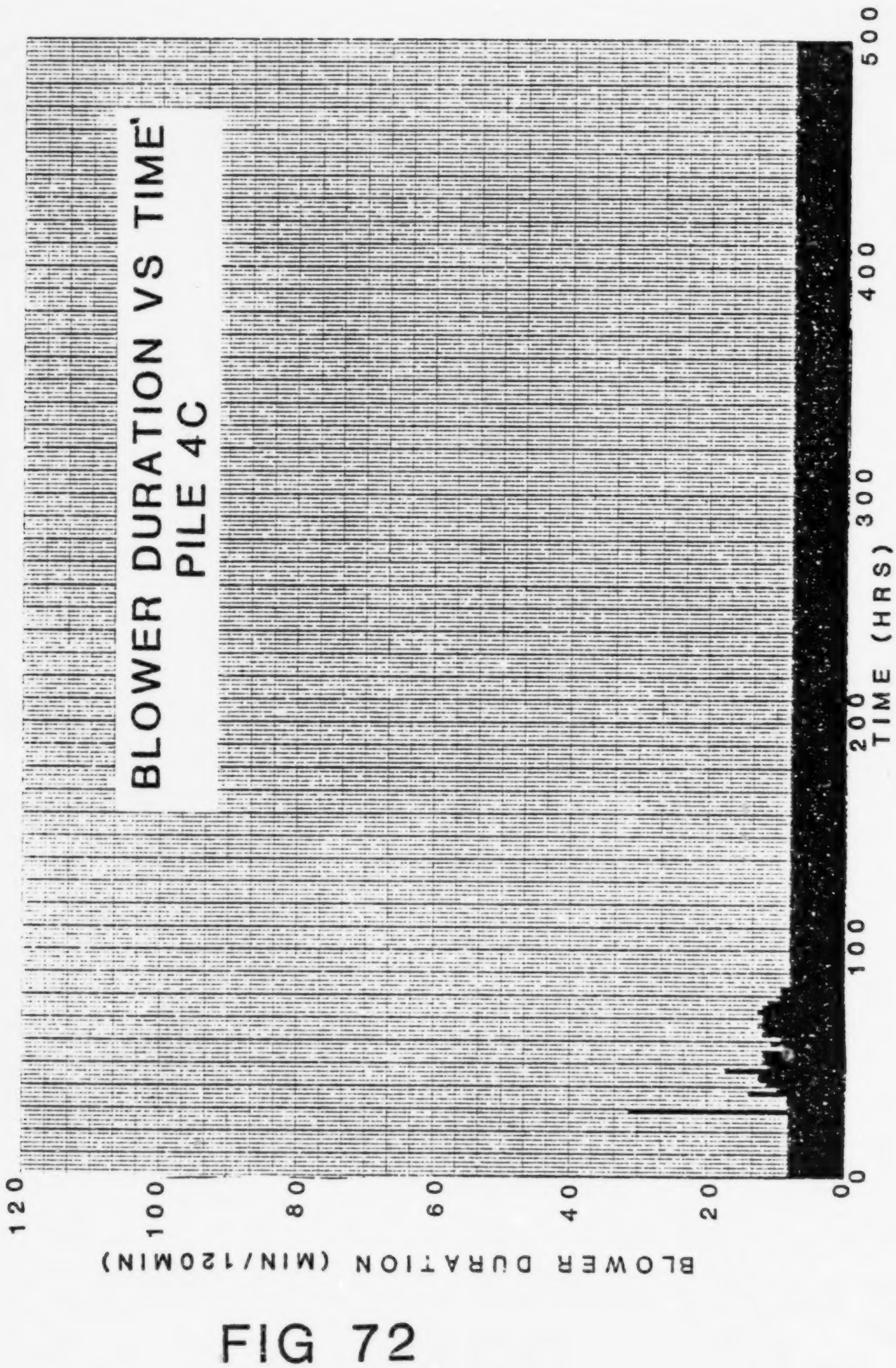

BLOWER DURATION VS TIME
PILE 4C
BLOWER DURATION (MIN/120MIN)
120
100
80
60
40
20
0
TIME (HRS)
0
100
200
300
400
500

FIG 72

TEMP. VS TIME: PILE4A ,PROBE #1,2

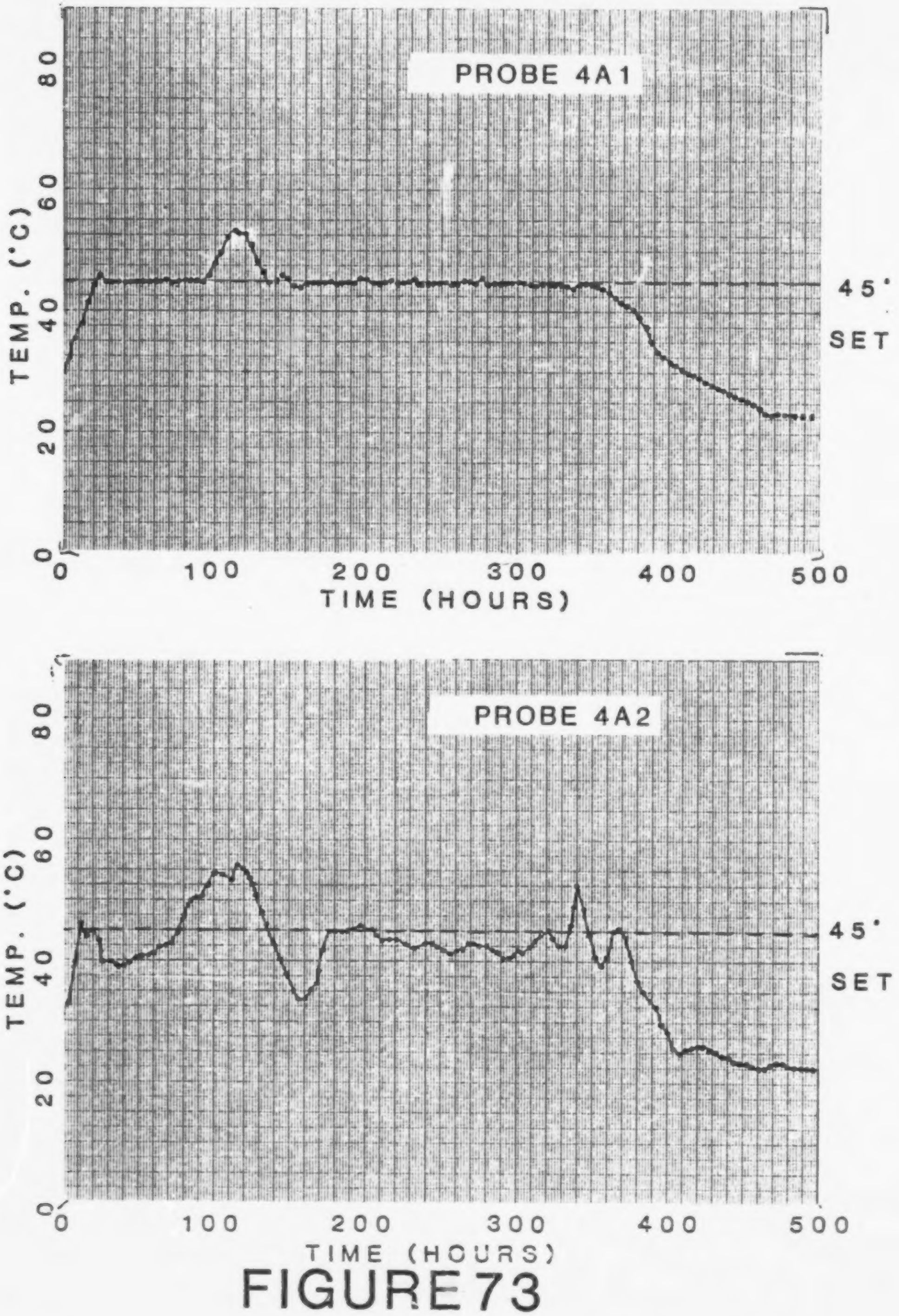
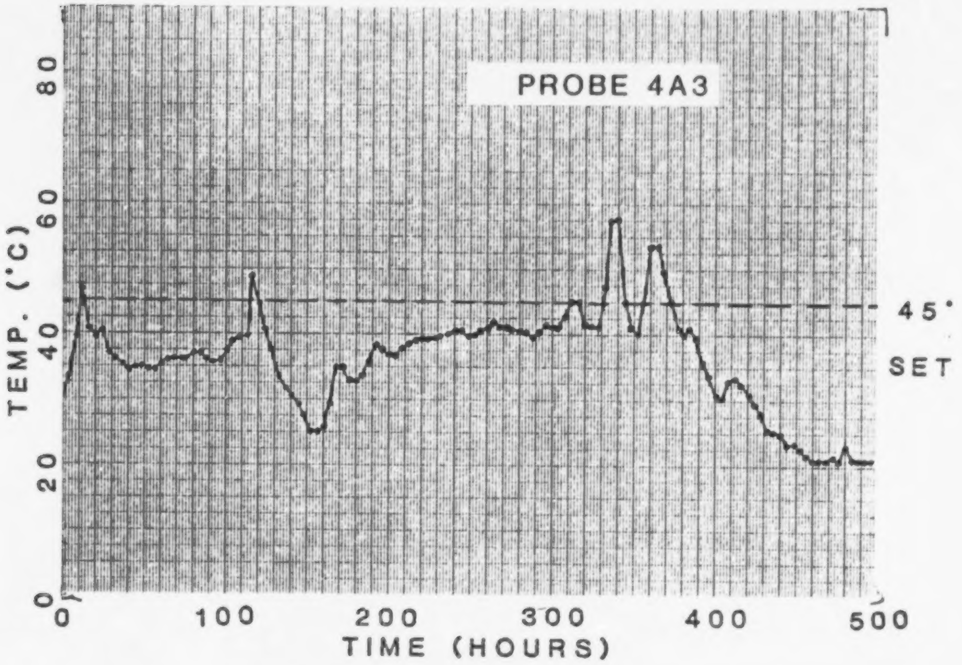


FIGURE 73

TEMP. VS TIME:
PILE4A ,PROBE #3,4



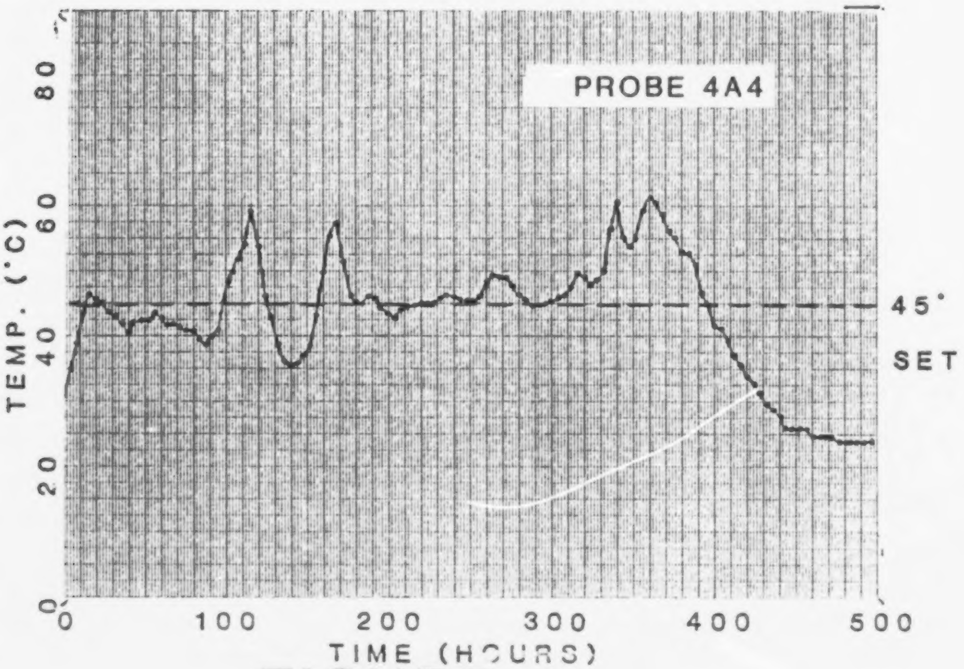


FIGURE 74

TEMP. VS TIME: PILE4A ,PROBE #5,6

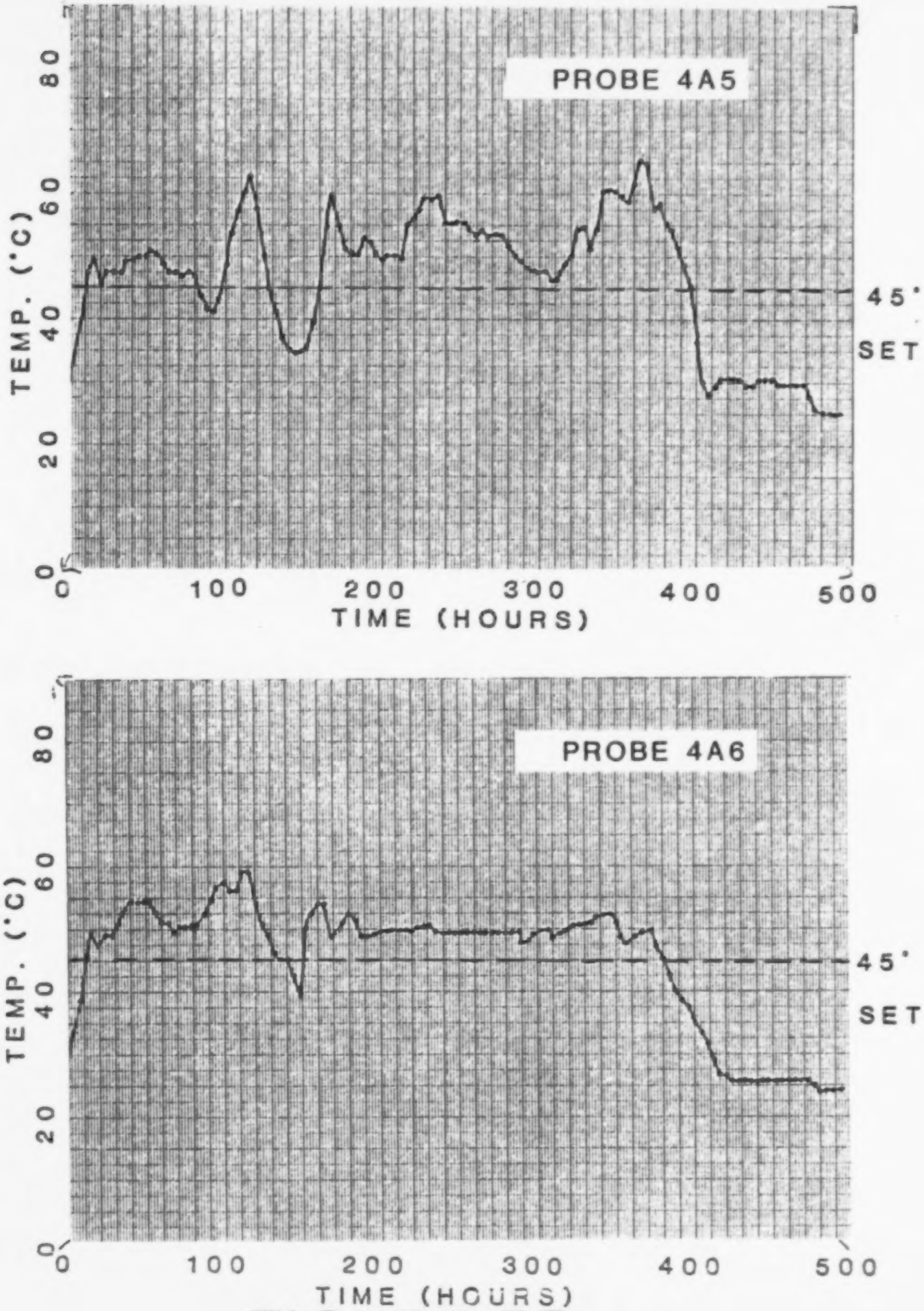


FIGURE 75

TEMP. VS TIME: PILE4A ,PROBE #7,8

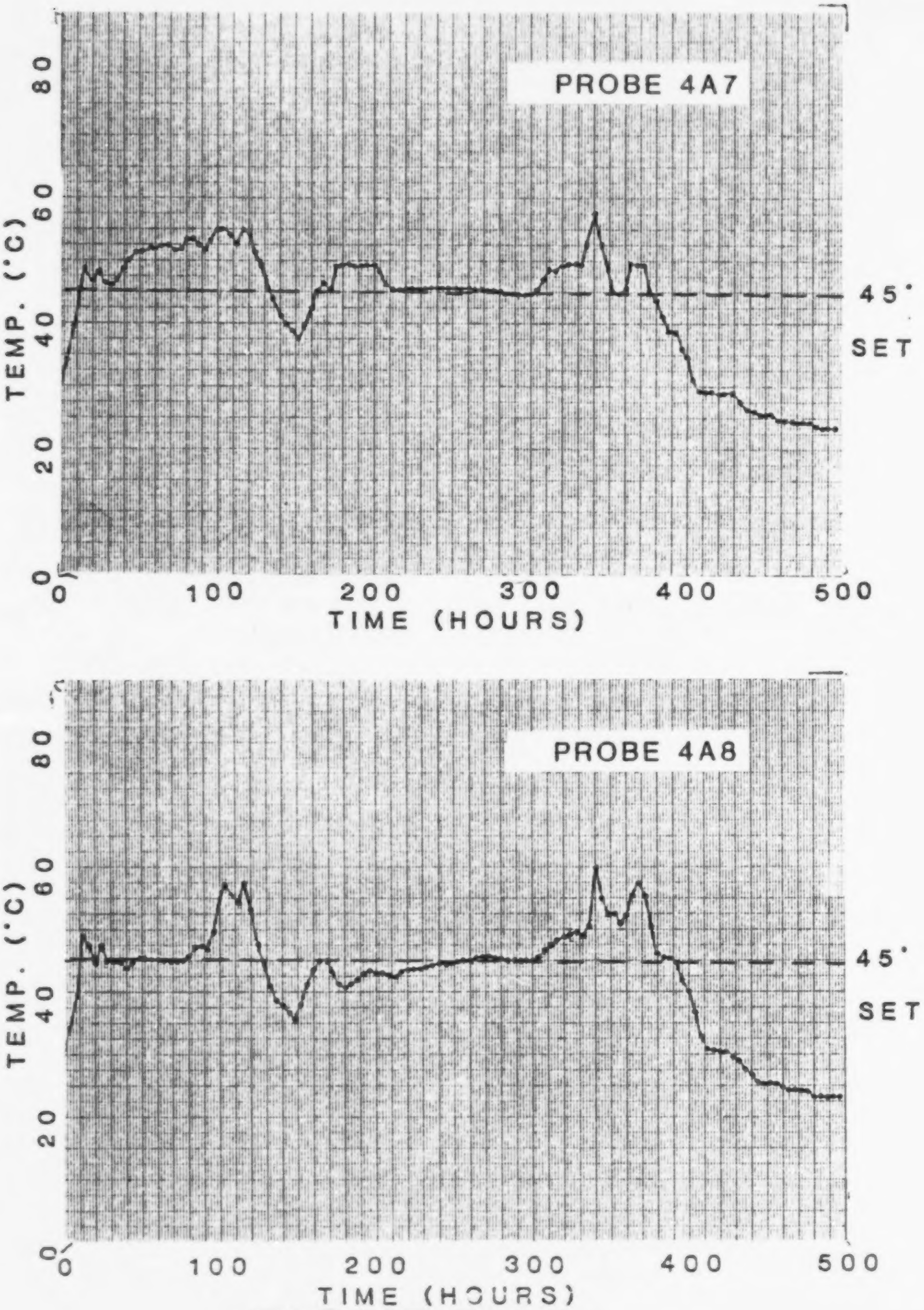
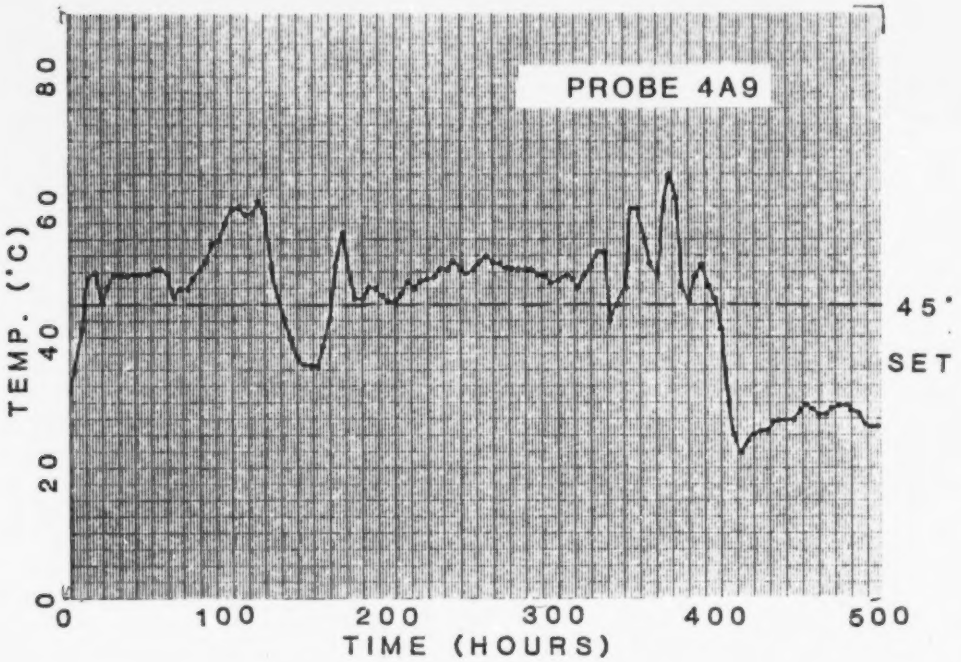


FIGURE 76

TEMP. VS TIME:
PILE4A ,PROBE #9,11



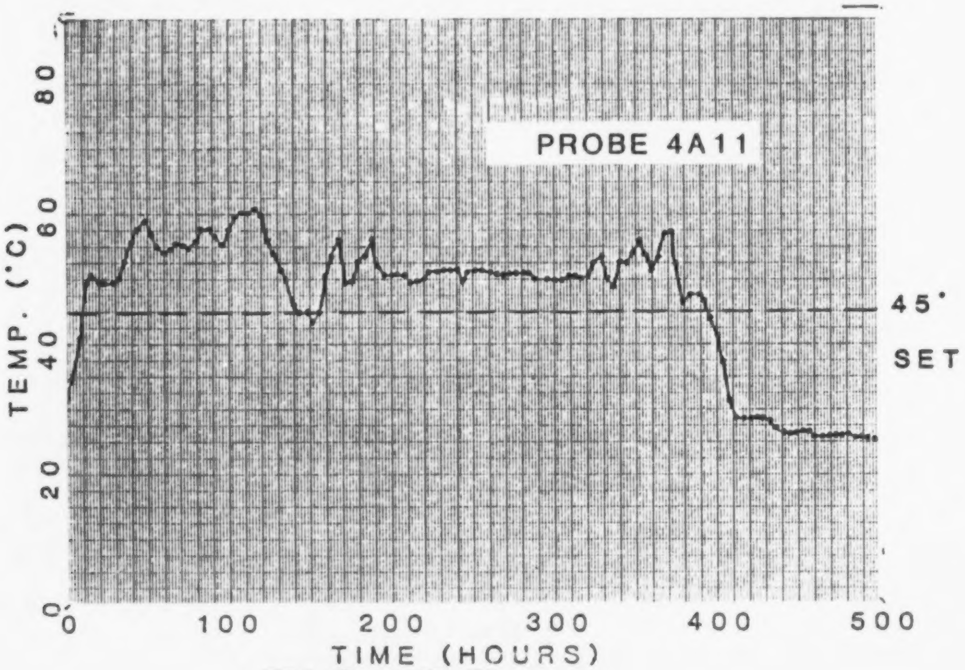


FIGURE 77

TEMP. VS TIME:
PILE4A ,PROBE #12,13

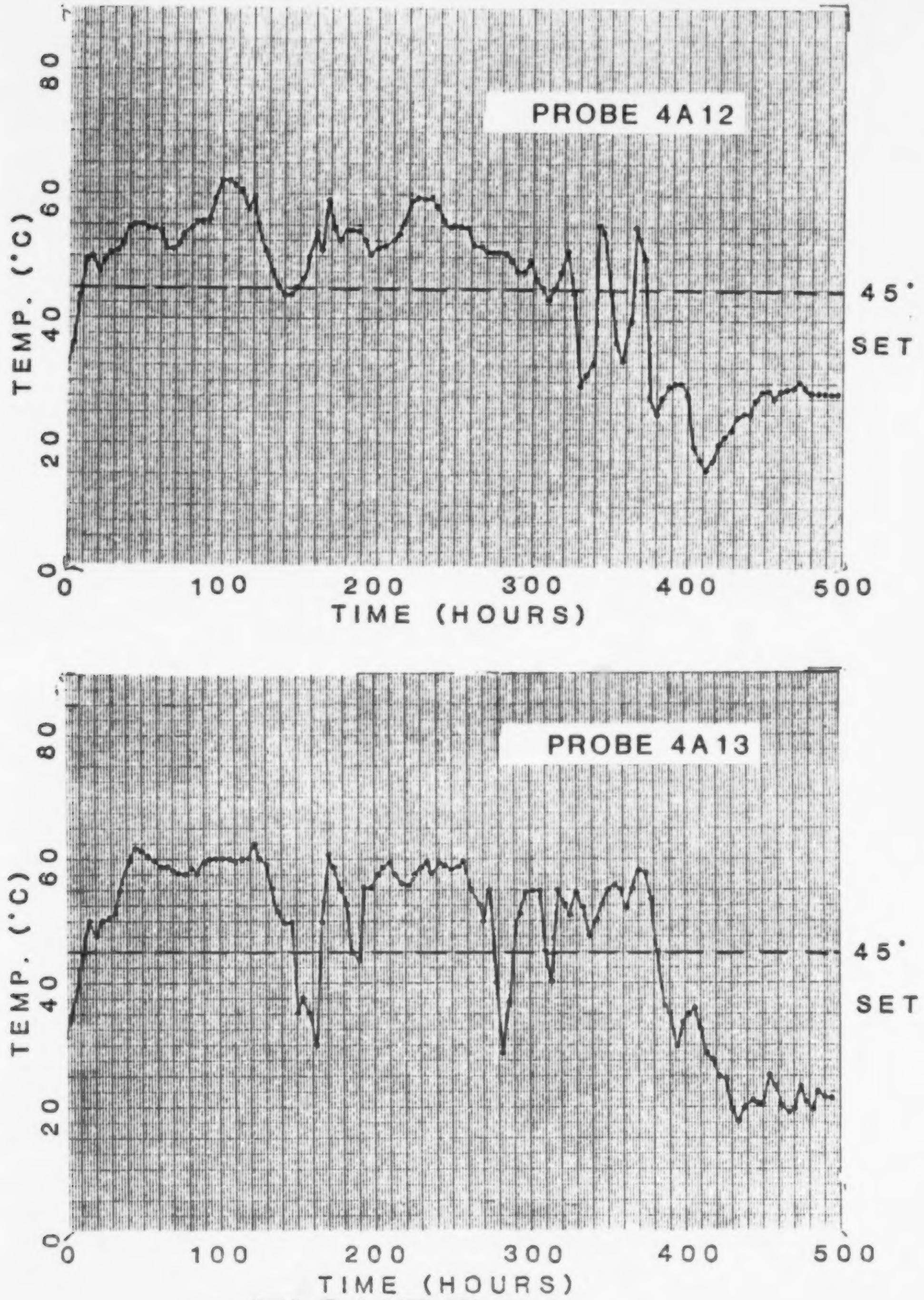


FIGURE 78

TEMP. VS TIME:
PILE 4B,PROBE #1,2

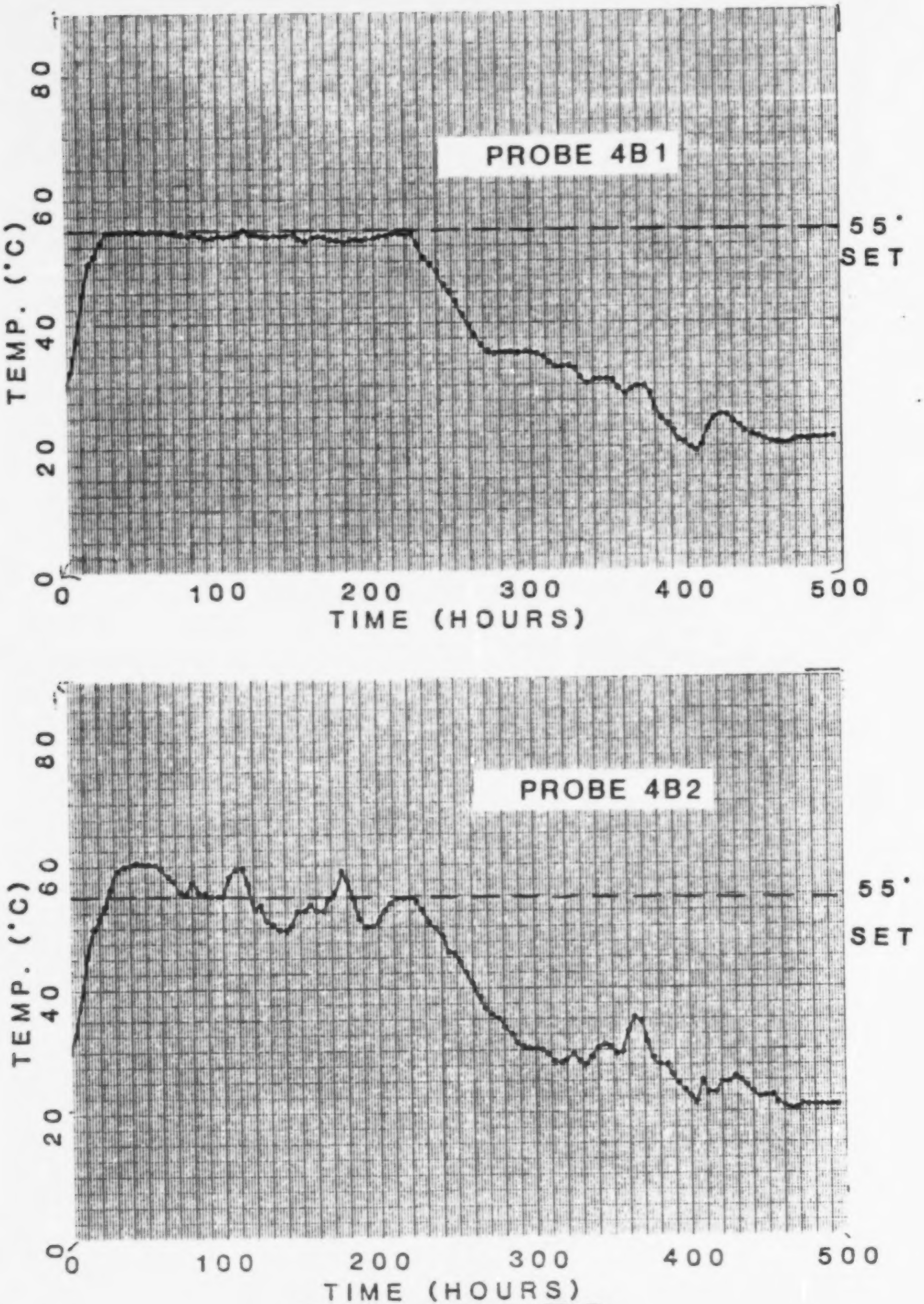


FIGURE 79

TEMP. VS TIME:
PILE 4B,PROBE #3,4

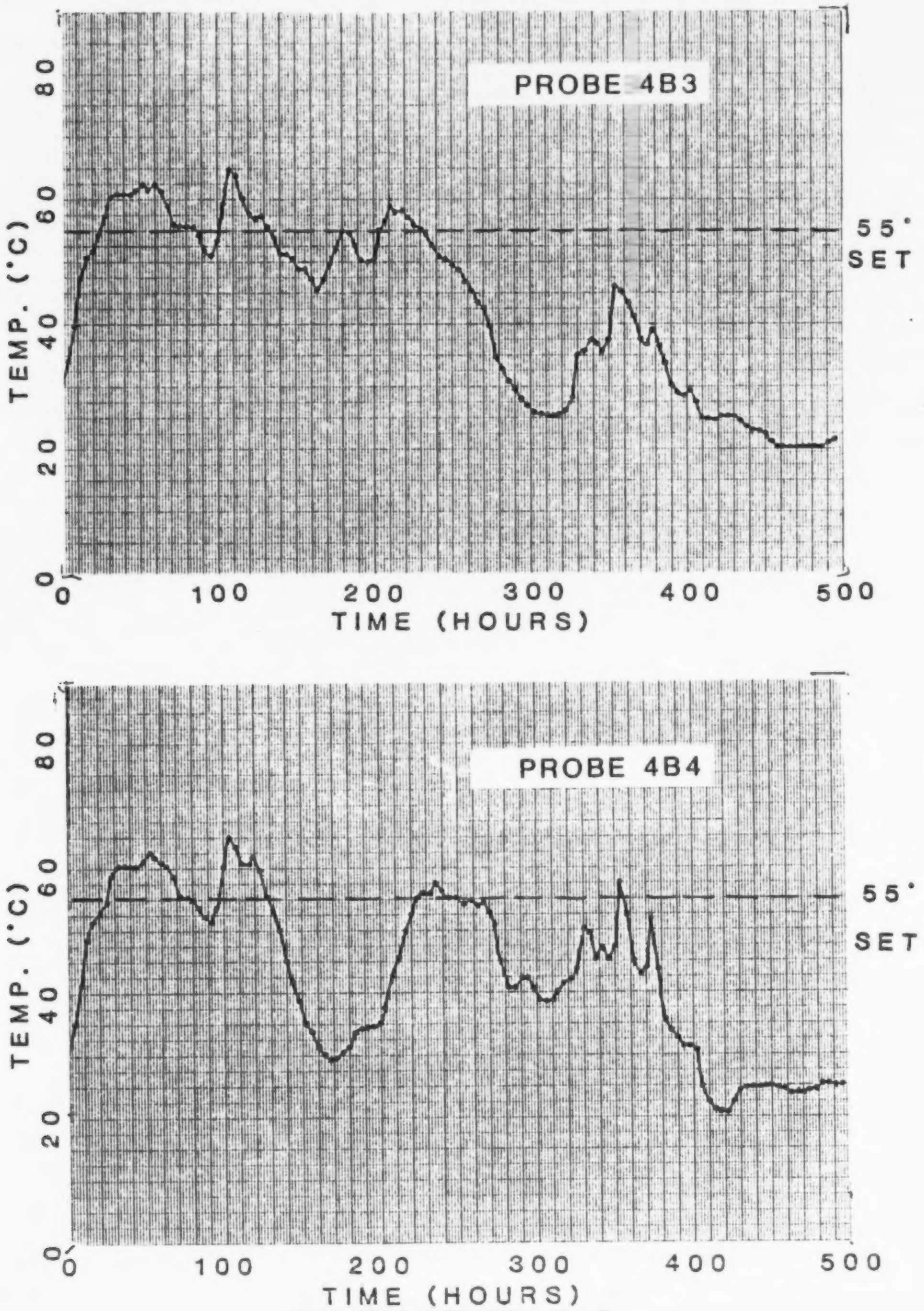
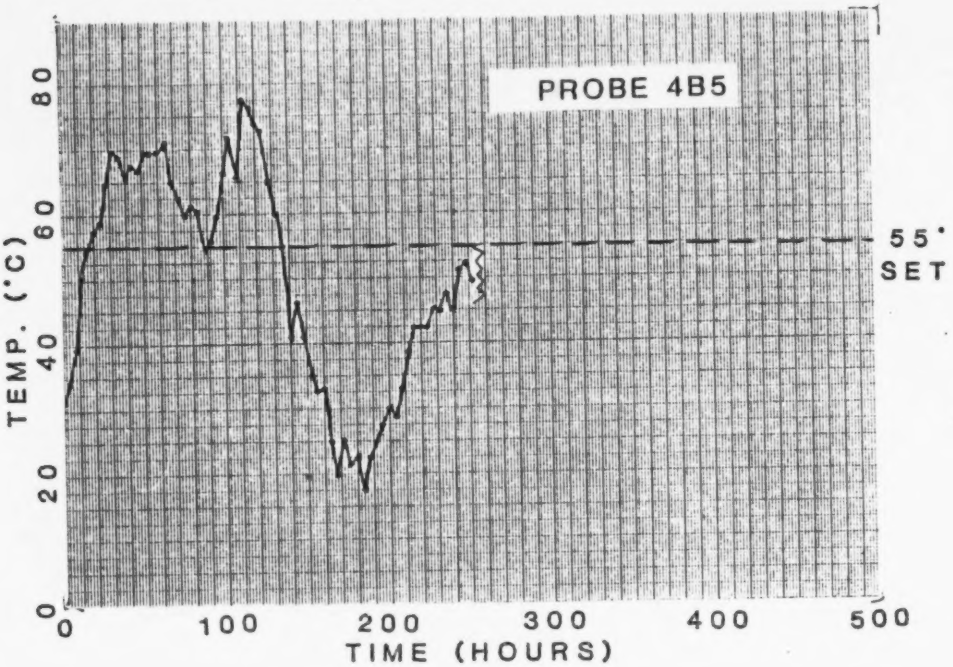


FIGURE 80

TEMP. VS TIME:
PILE 4B,PROBE #5,6



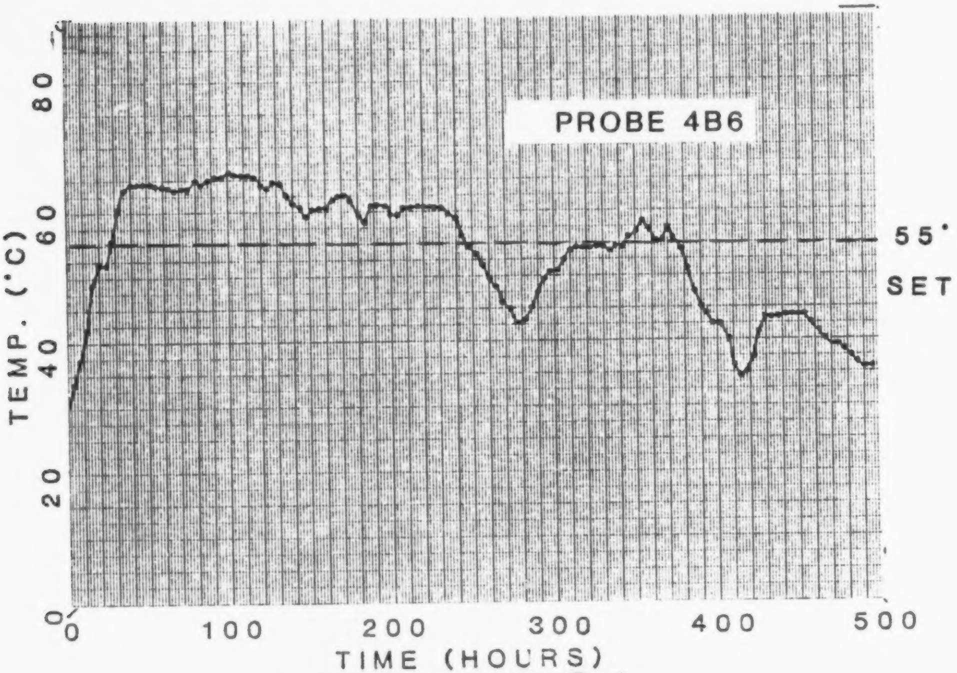


FIGURE 81

TEMP. VS TIME: PILE 4B,PROBE #7,8

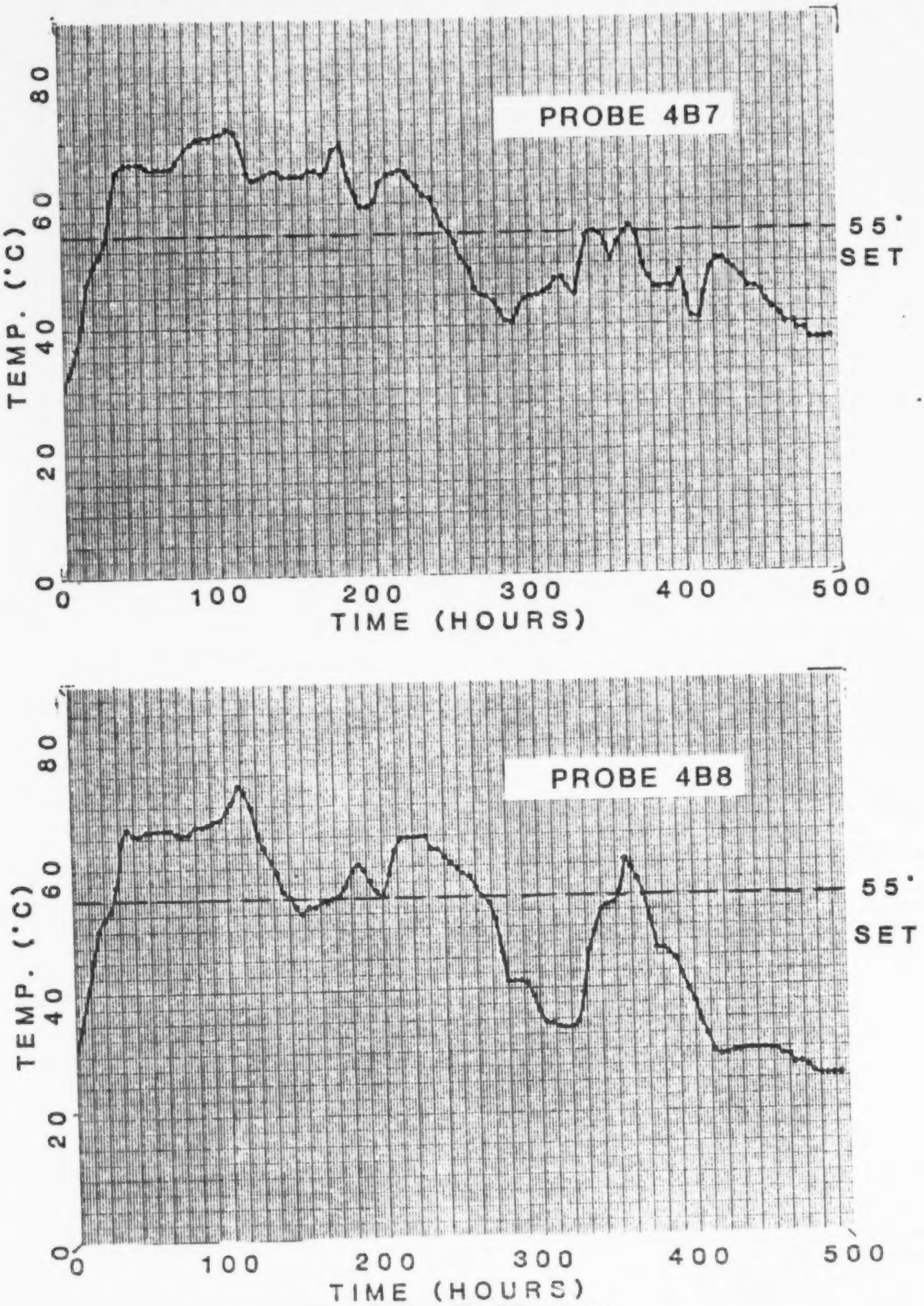


FIGURE 82

TEMP. VS TIME: PILE 4B,PROBE#9,10

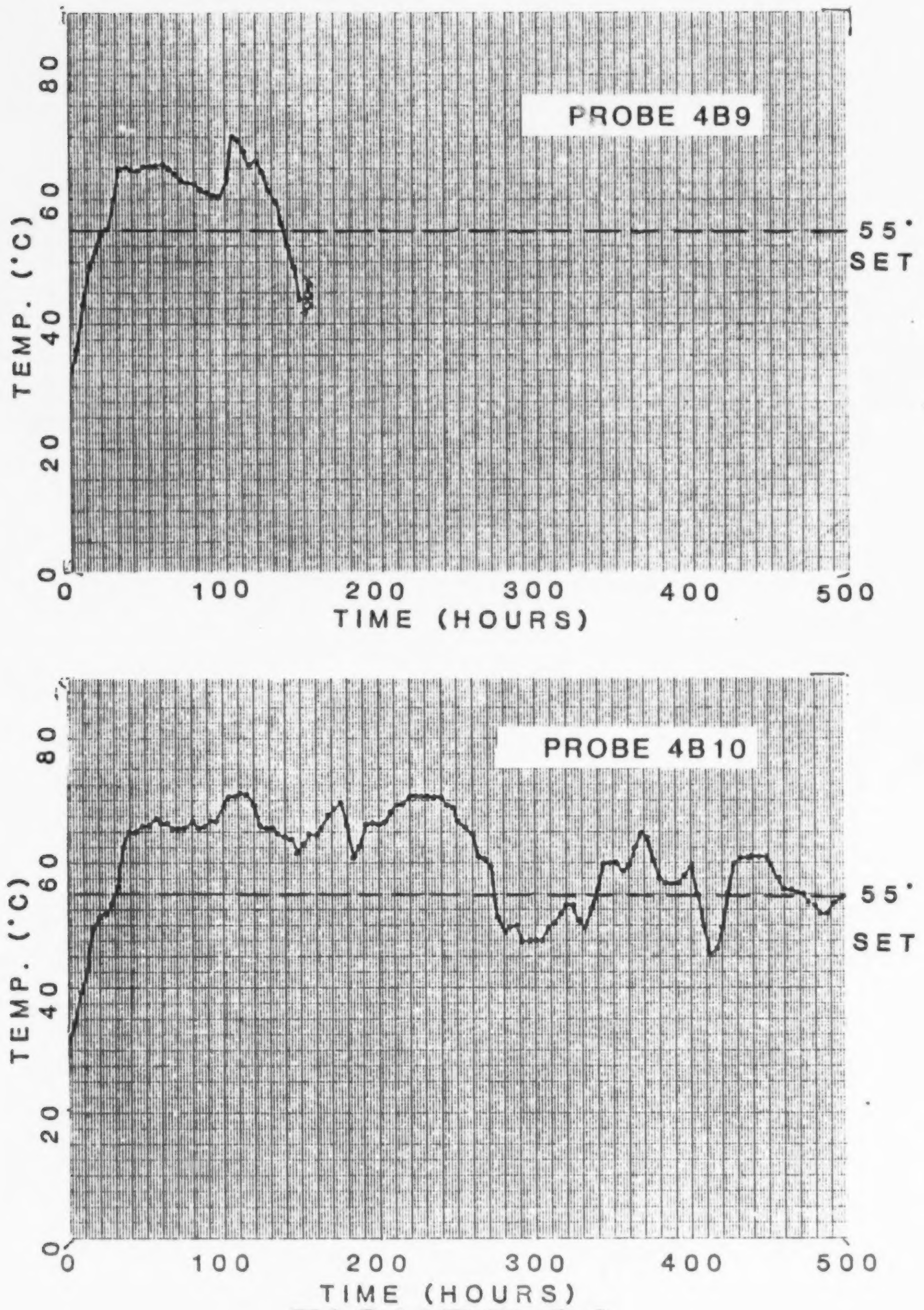


FIGURE 83

TEMP. VS TIME: PILE 4B,PROBE #11,12

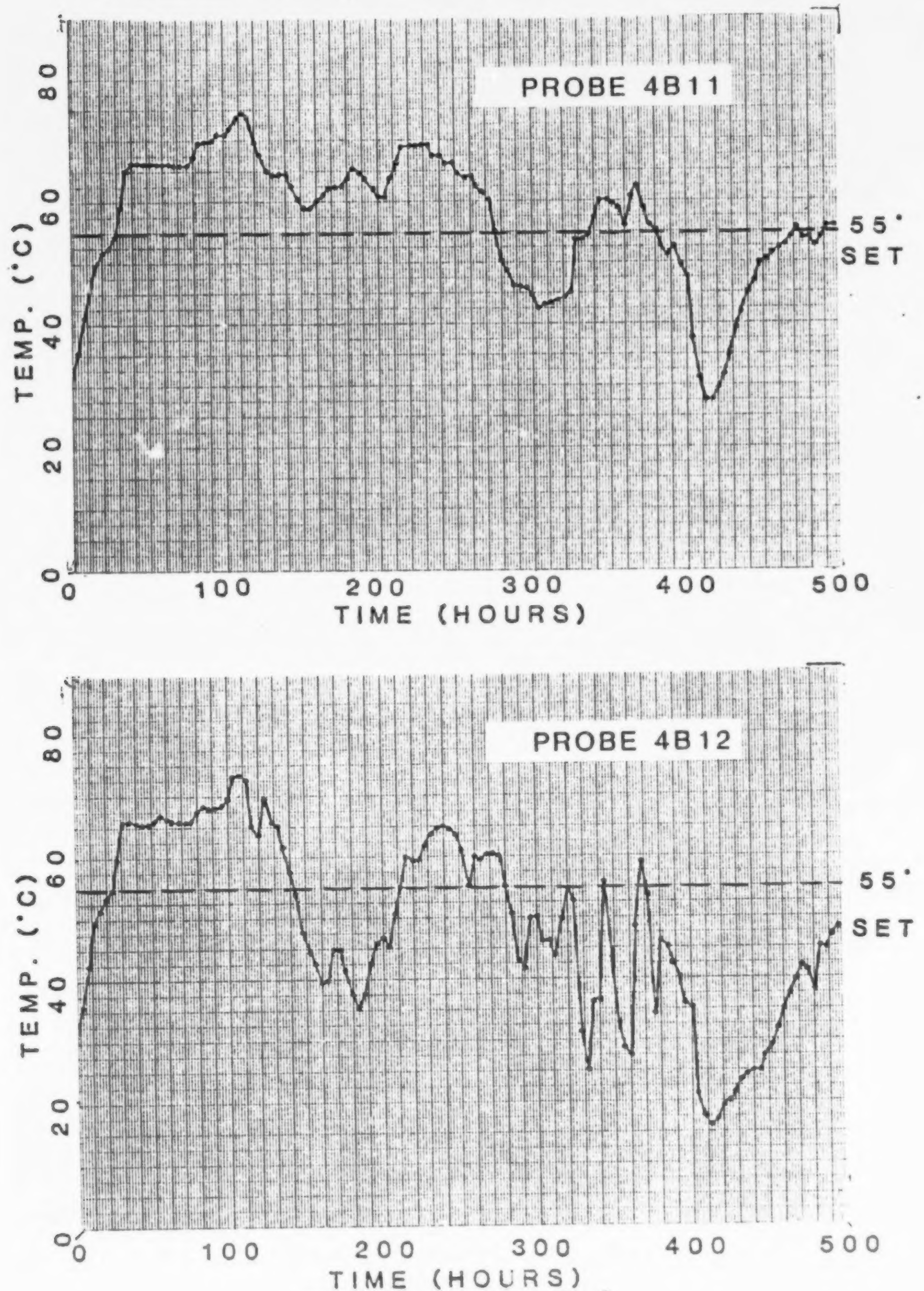


FIGURE 84

TEMP. VS TIME: PILE 4B,PROBE #13,14

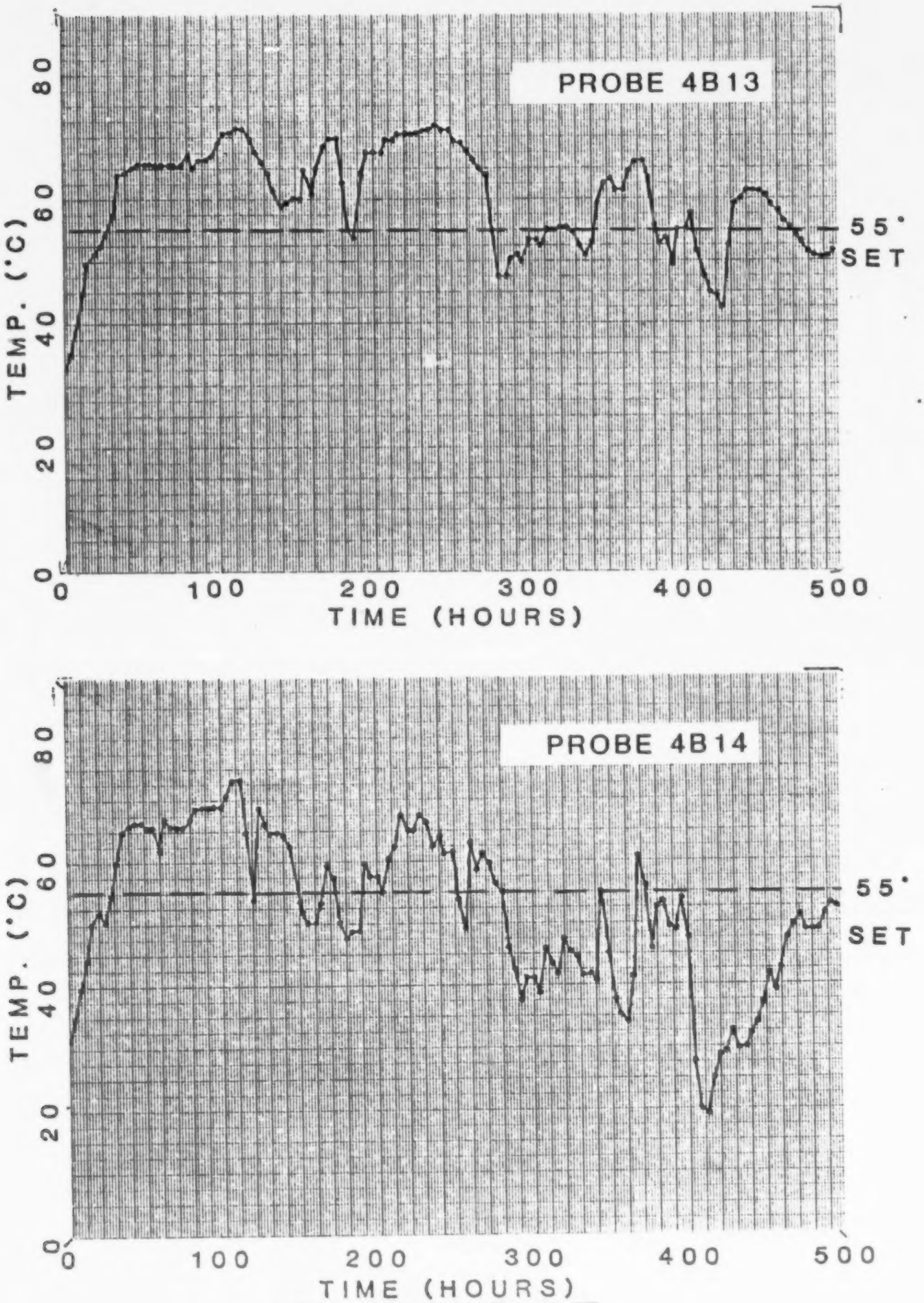


FIGURE 85

TEMP. VS TIME:
PILE 4C,PROBE #1,2

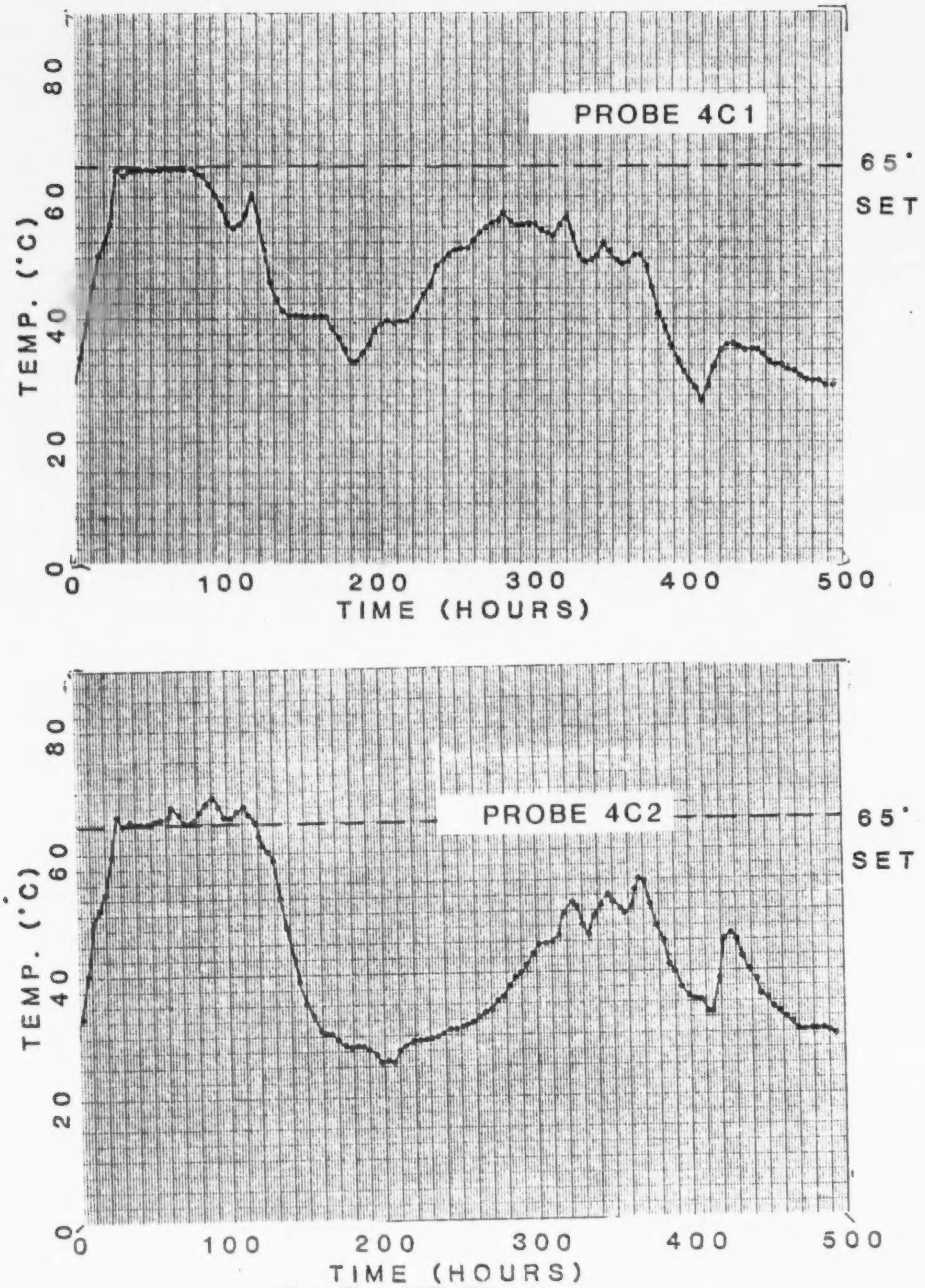


FIGURE 86

TEMP. VS TIME:
PILE 4C,PROBE #3,4

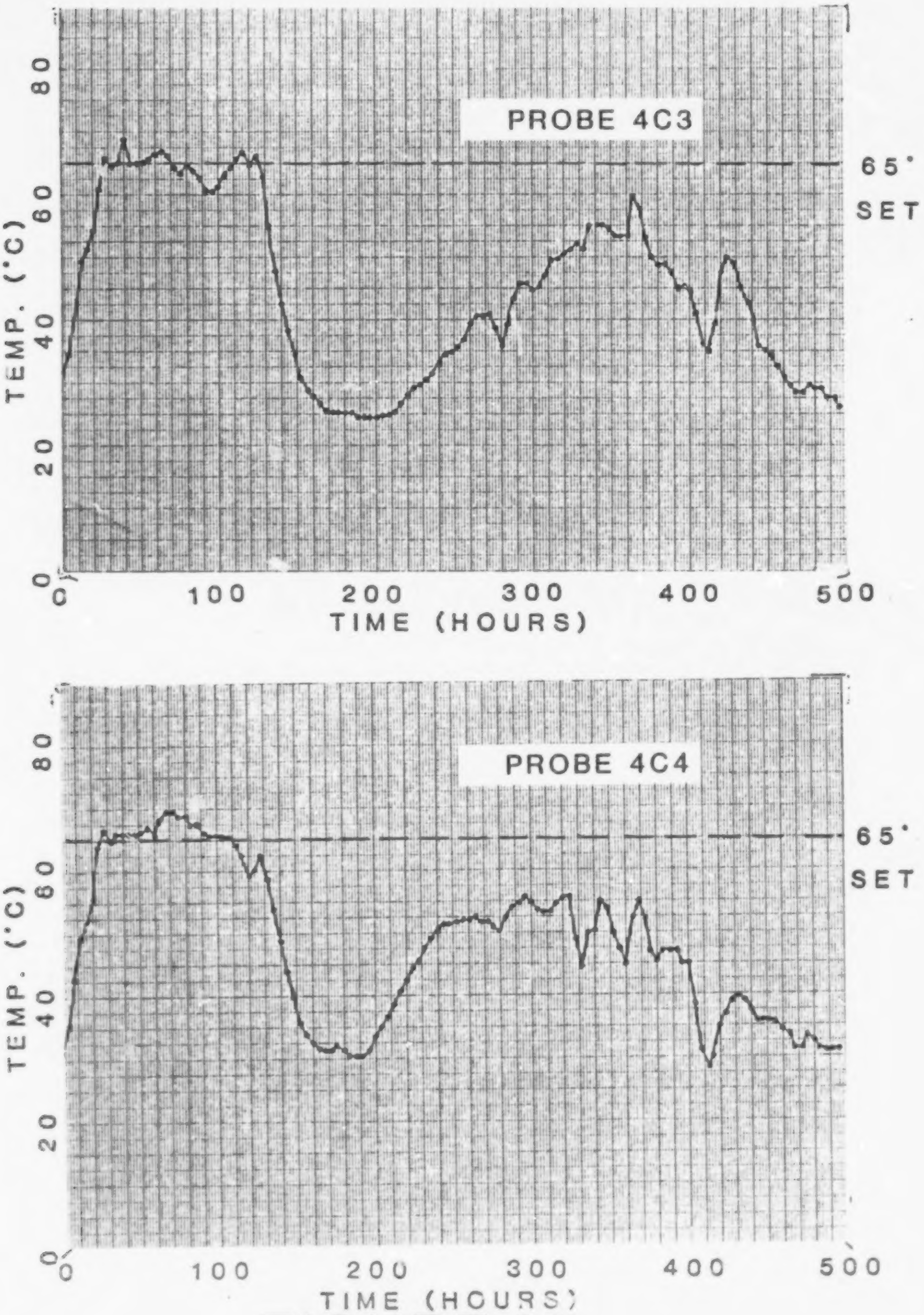


FIGURE 87

TEMP. VS TIME:
PILE 4C,PROBE #5,6

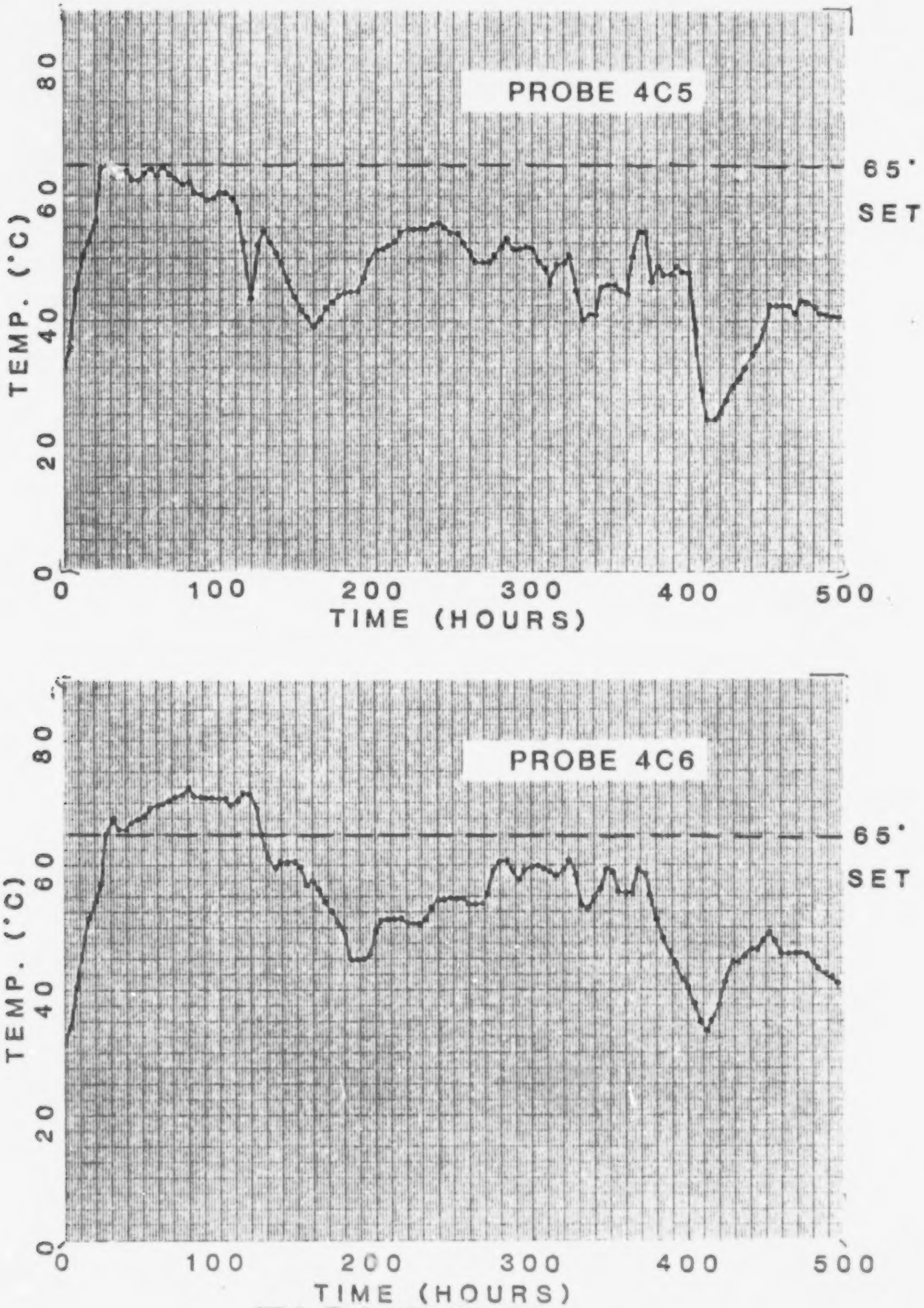


FIGURE 88

TEMP. VS TIME: PILE 4C,PROBE #7,8

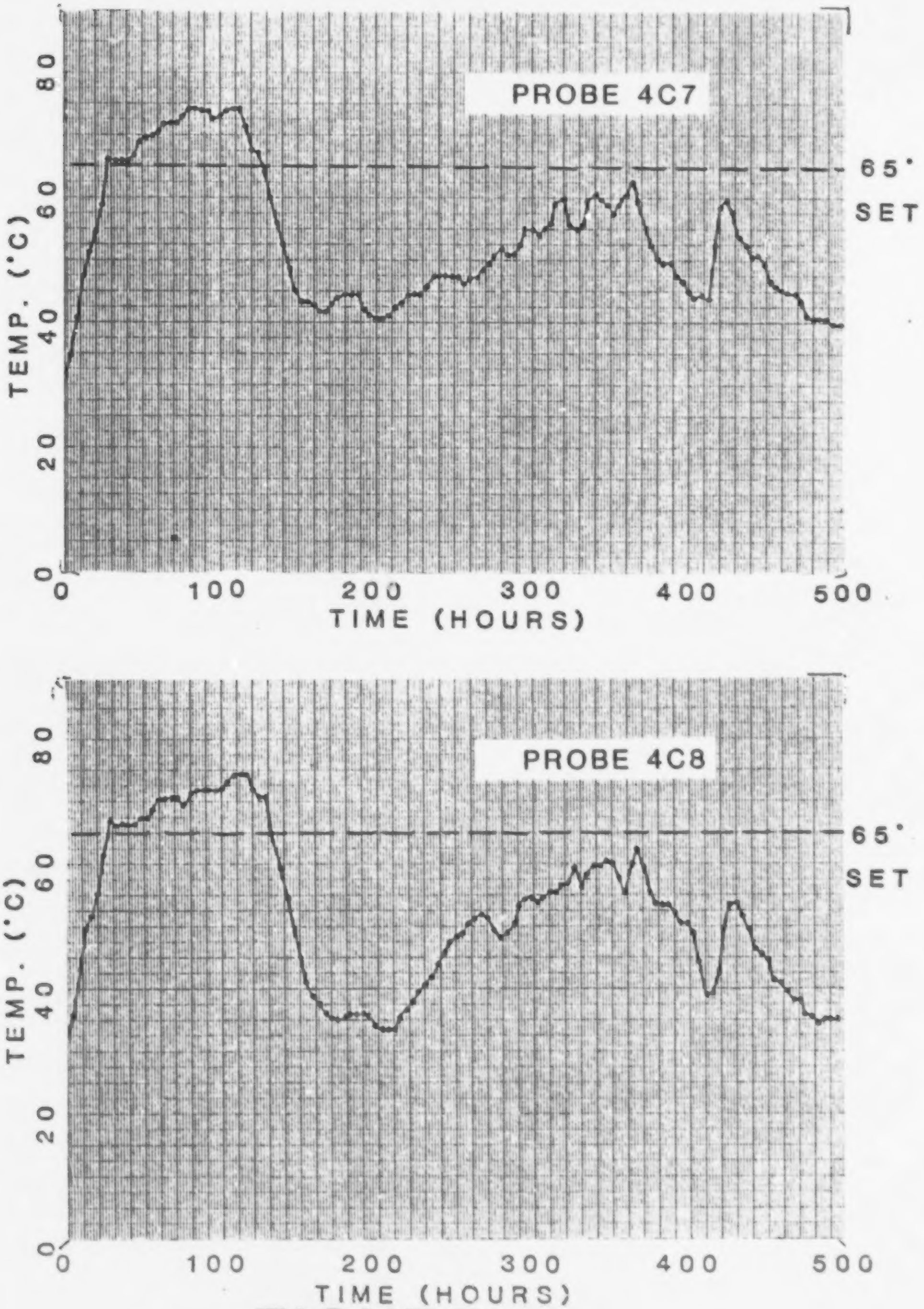


FIGURE 89

TEMP. VS TIME:
PILE 4C, PROBE #9, 10

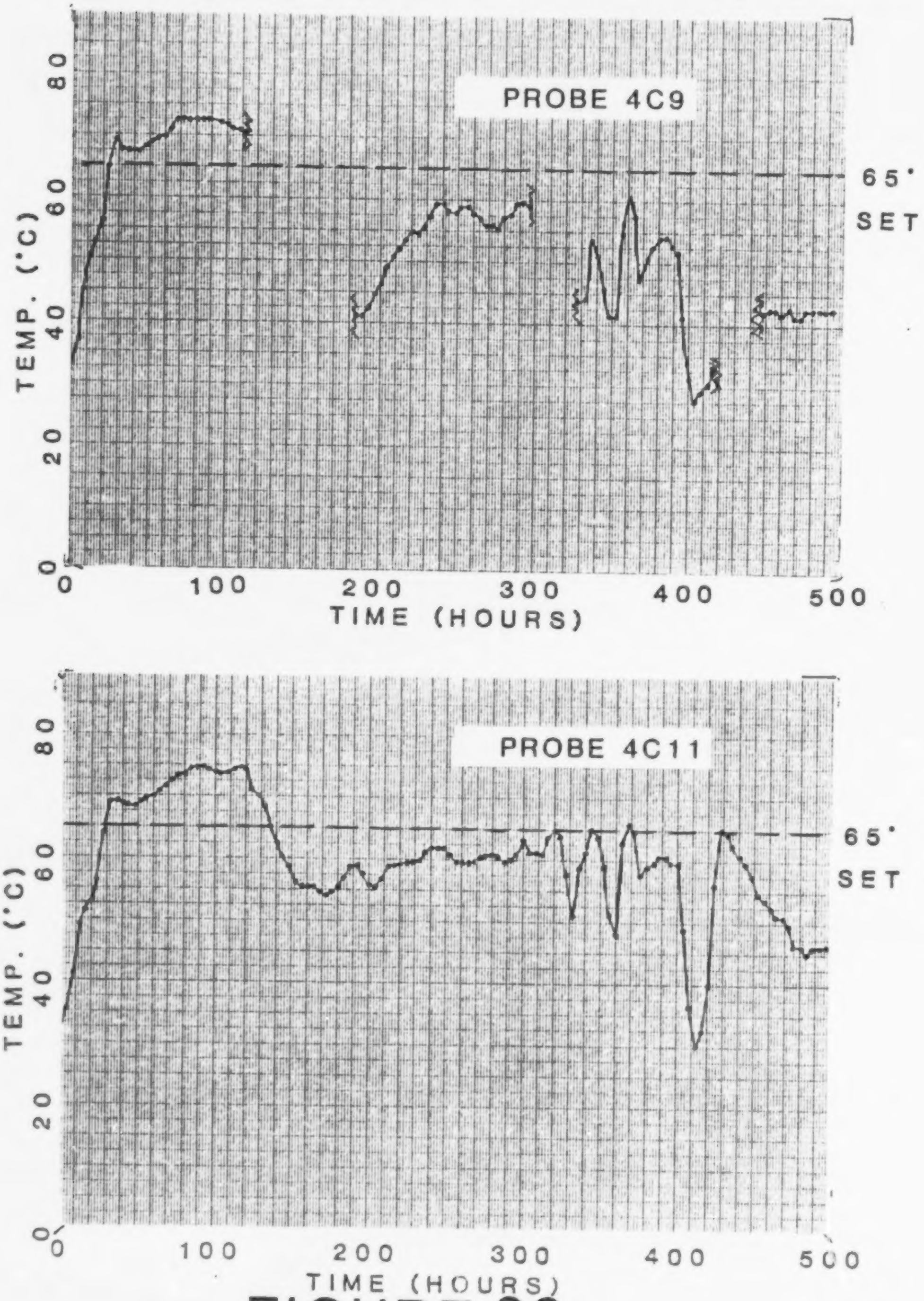


FIGURE 90

TEMP. VS TIME: PILE 4C,PROBE #12,13

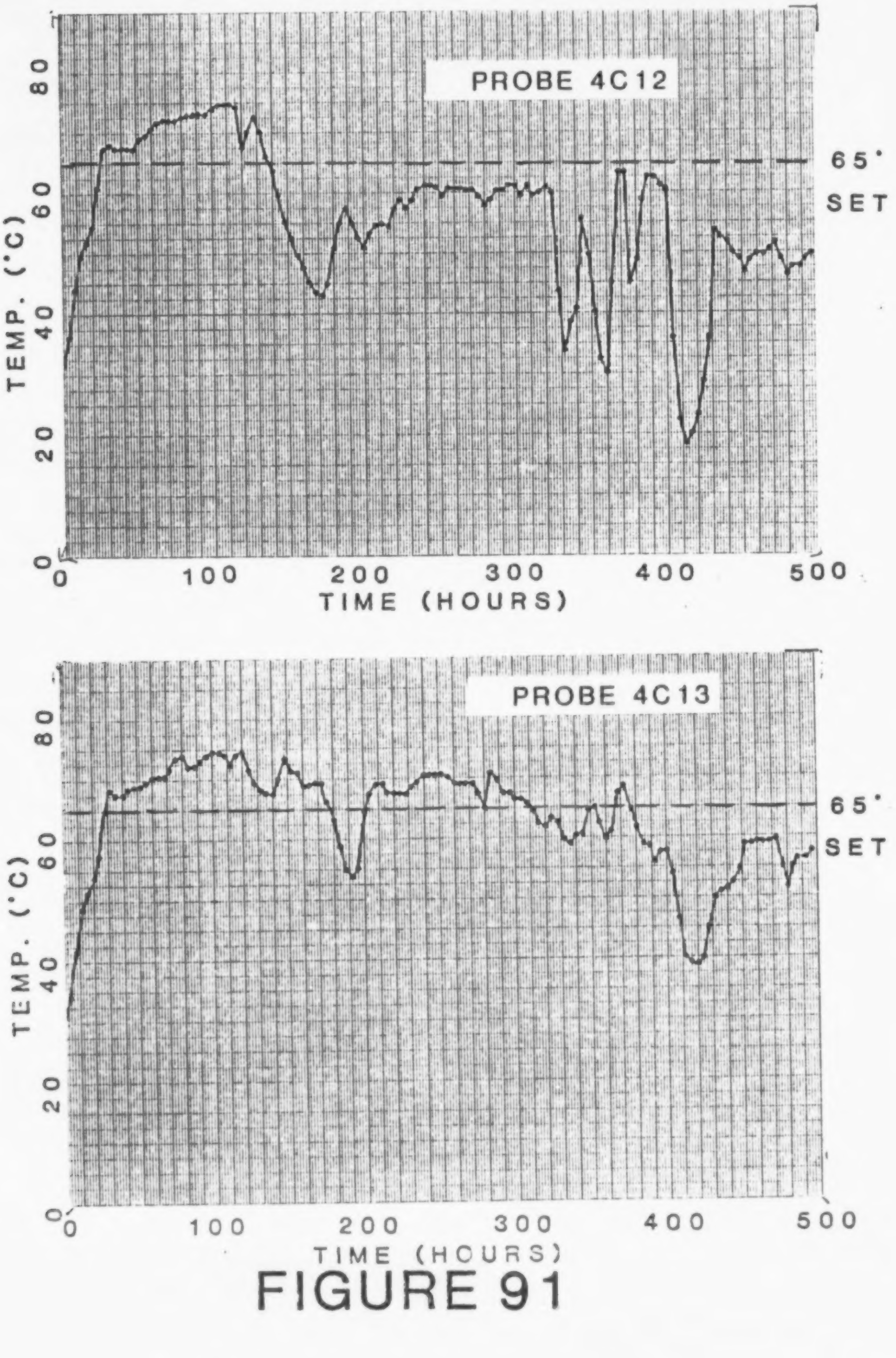


FIGURE 91

TEMP. VS TIME:
PILE 4C,PROBE #14

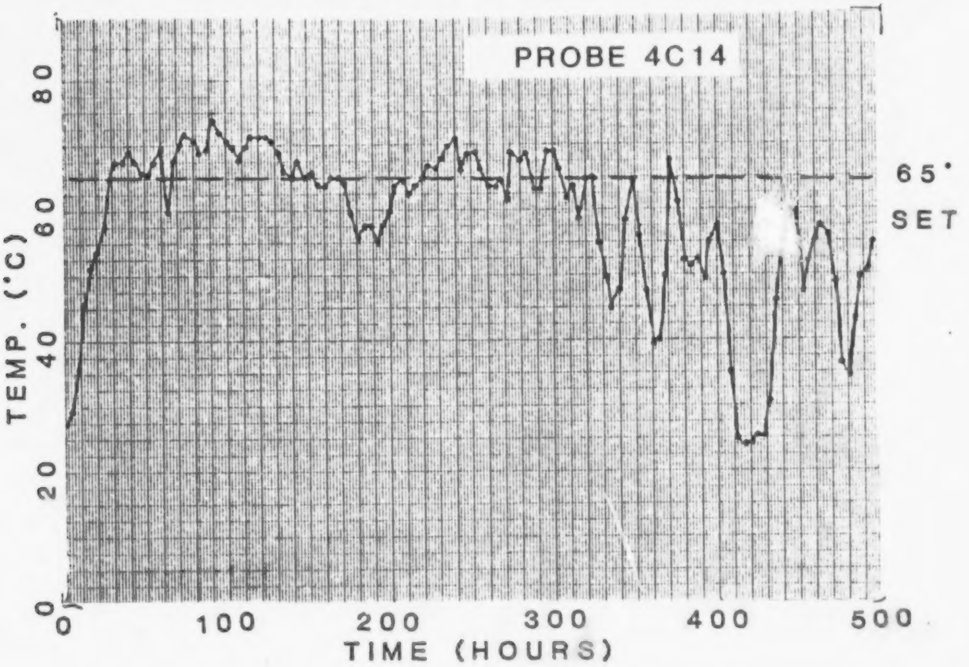


FIGURE 92

% CO2 VS TIME-PILE 4A,4B

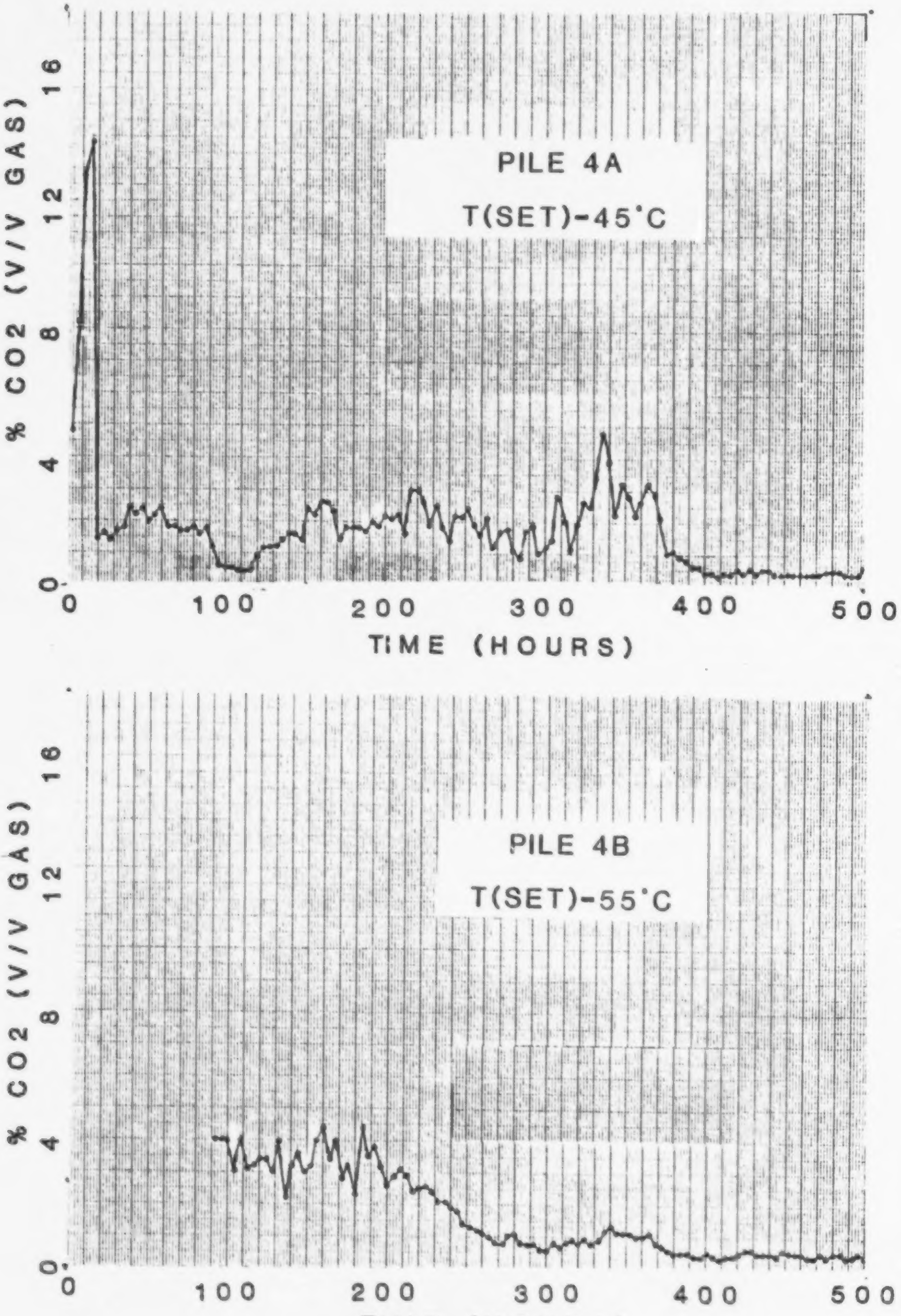


FIG 93

% CO2 VS TIME-PILE 4C

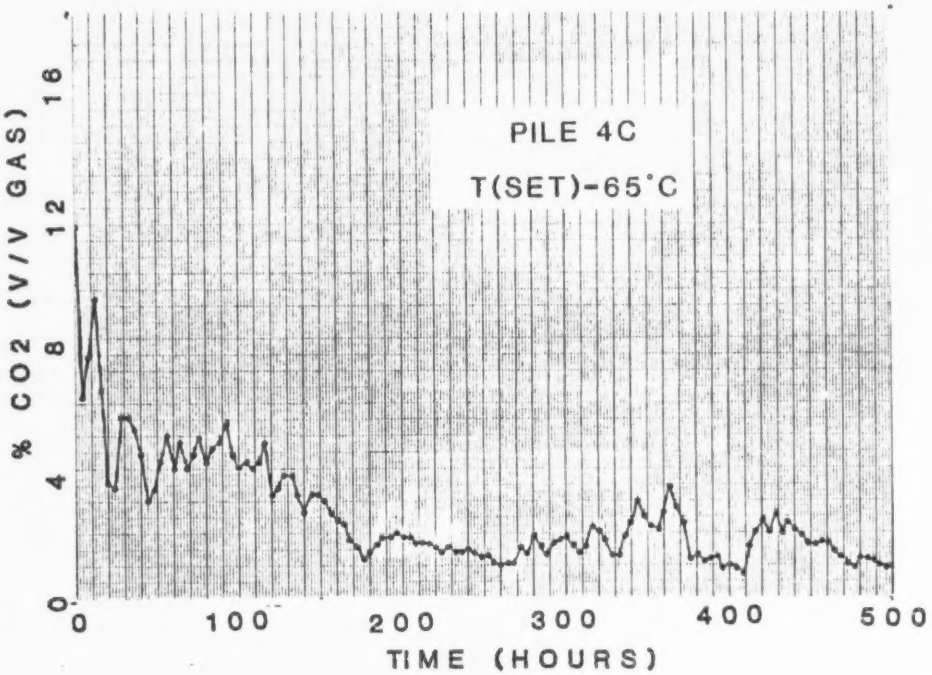


FIG 94

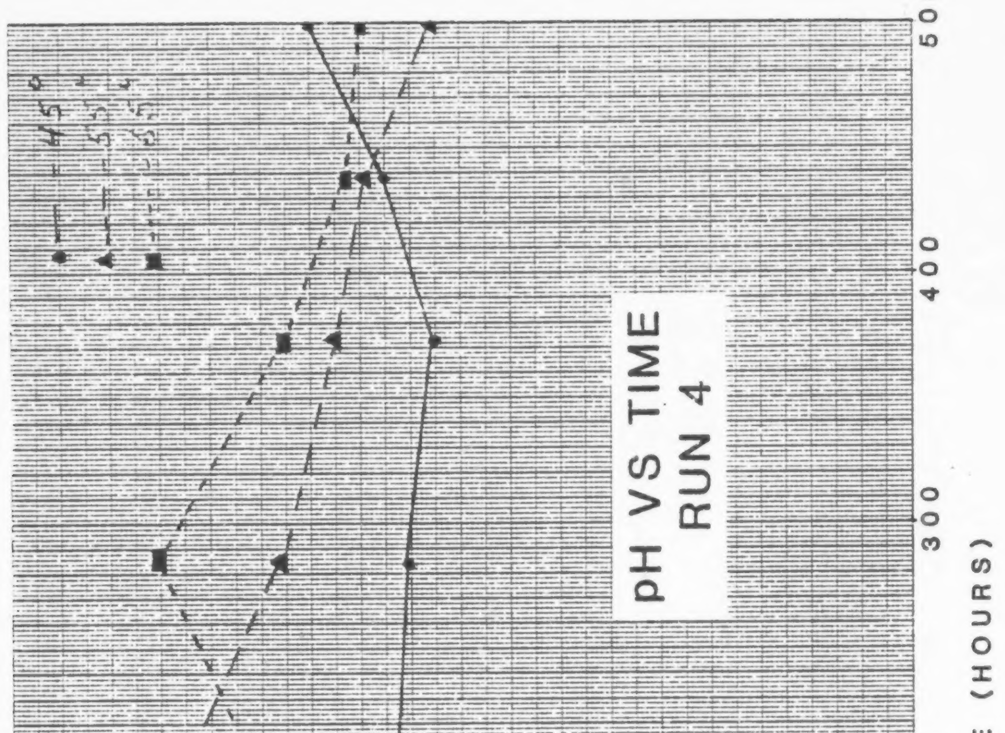

pH VS TIME
RUN 4
45°
55°
65°
pH
9
8
7
6
5
0
100
200
300
400
500
TIME (HOURS)

FIG 95

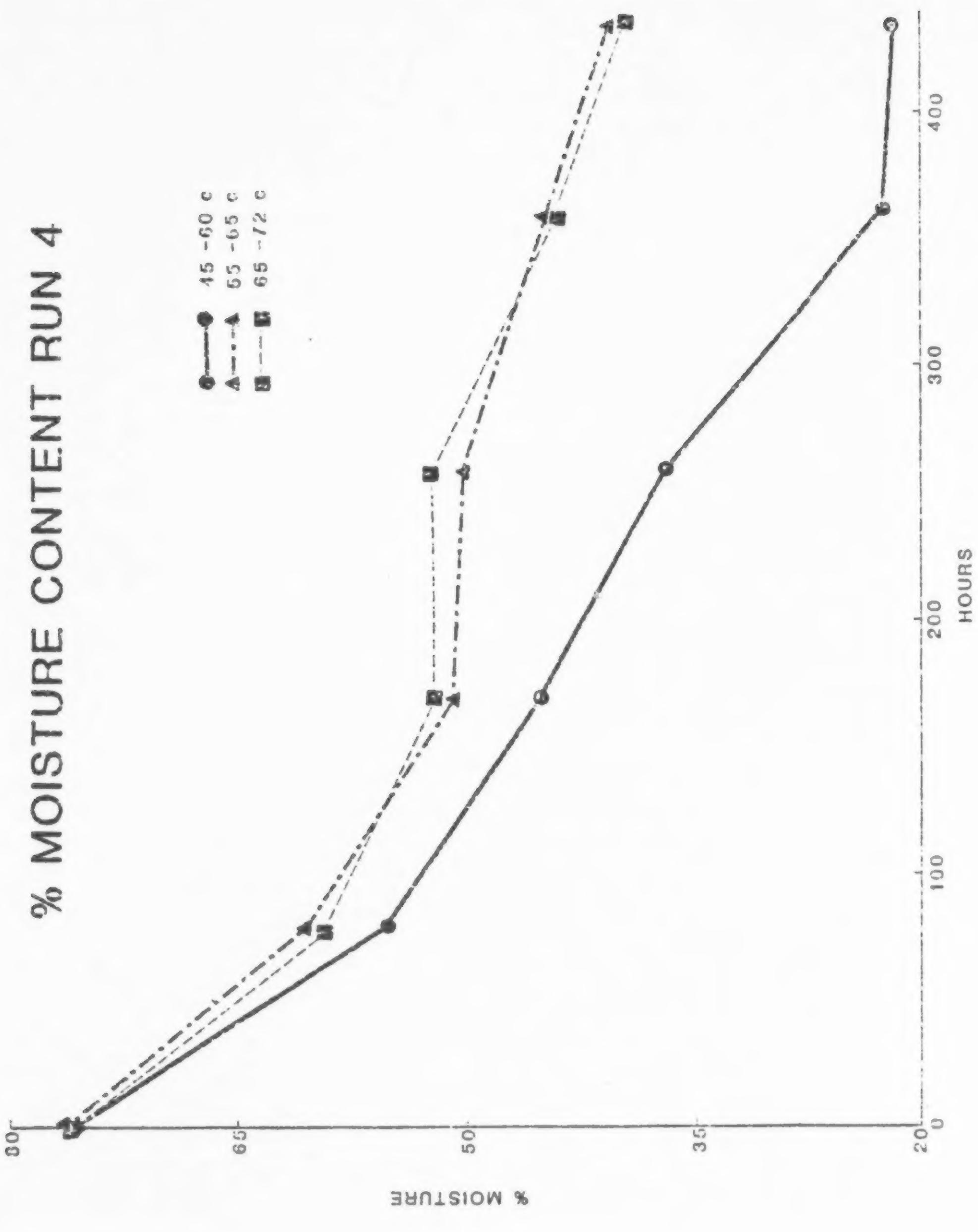

% MOISTURE CONTENT RUN 4
45 -60 c
55 -65 c
65 -72 c
% MOISTURE
80
65
50
35
20
HOURS
0
100
200
300
400

FIG 96

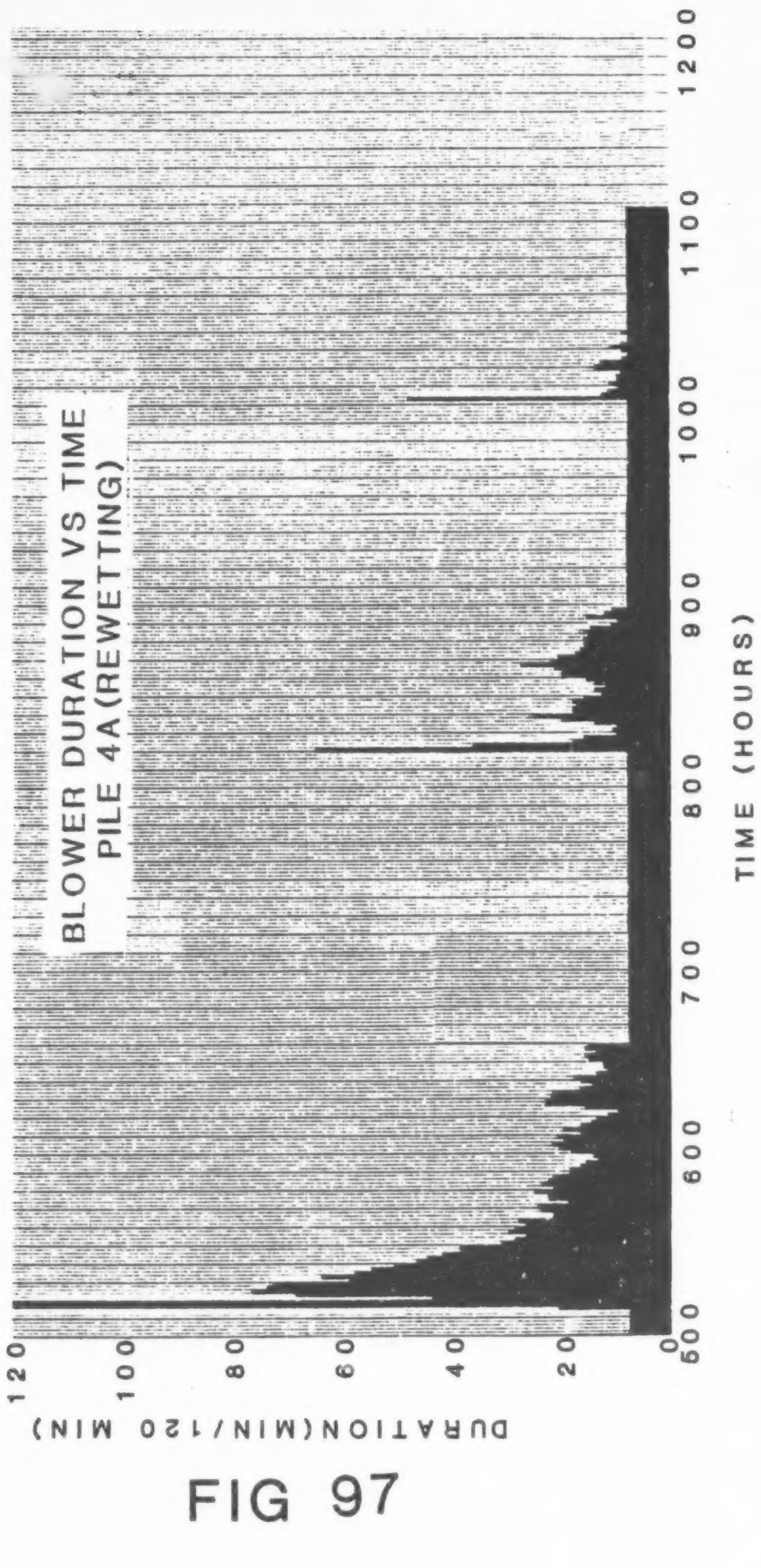

BLOWER DURATION VS TIME
PILE 4A(REWETTING)
DURATION(MIN/120 MIN)
120
100
80
60
40
20
0
500
600
700
800
900
1000
1100
1200
TIME (HOURS)

FIG 97

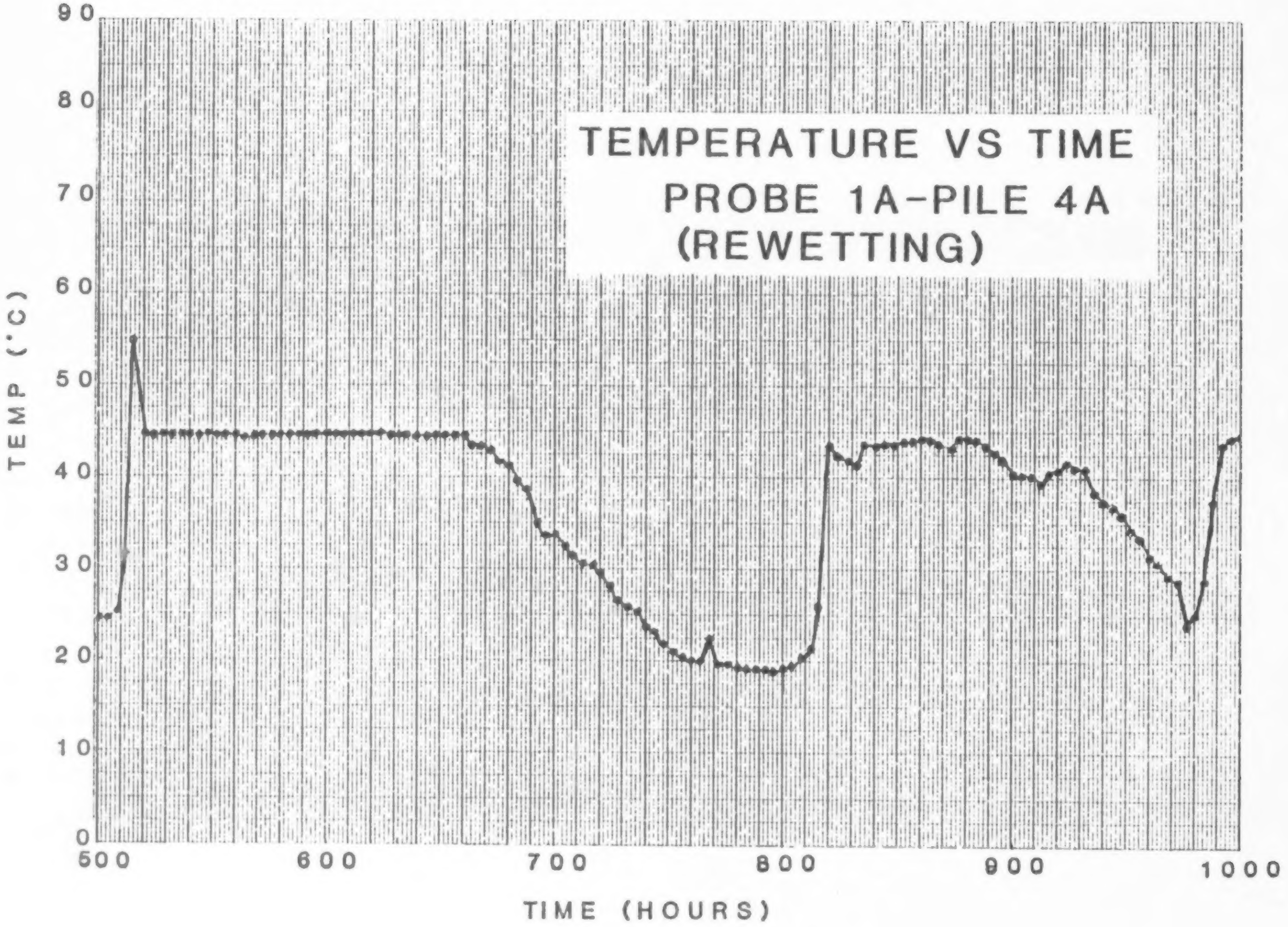

TEMPERATURE VS TIME
PROBE 1A-PILE 4A
(REWETTING)
TEMP (°C)
0
10
20
30
40
50
60
70
80
90
500
600
700
800
900
1000
TIME (HOURS)

FIG 98

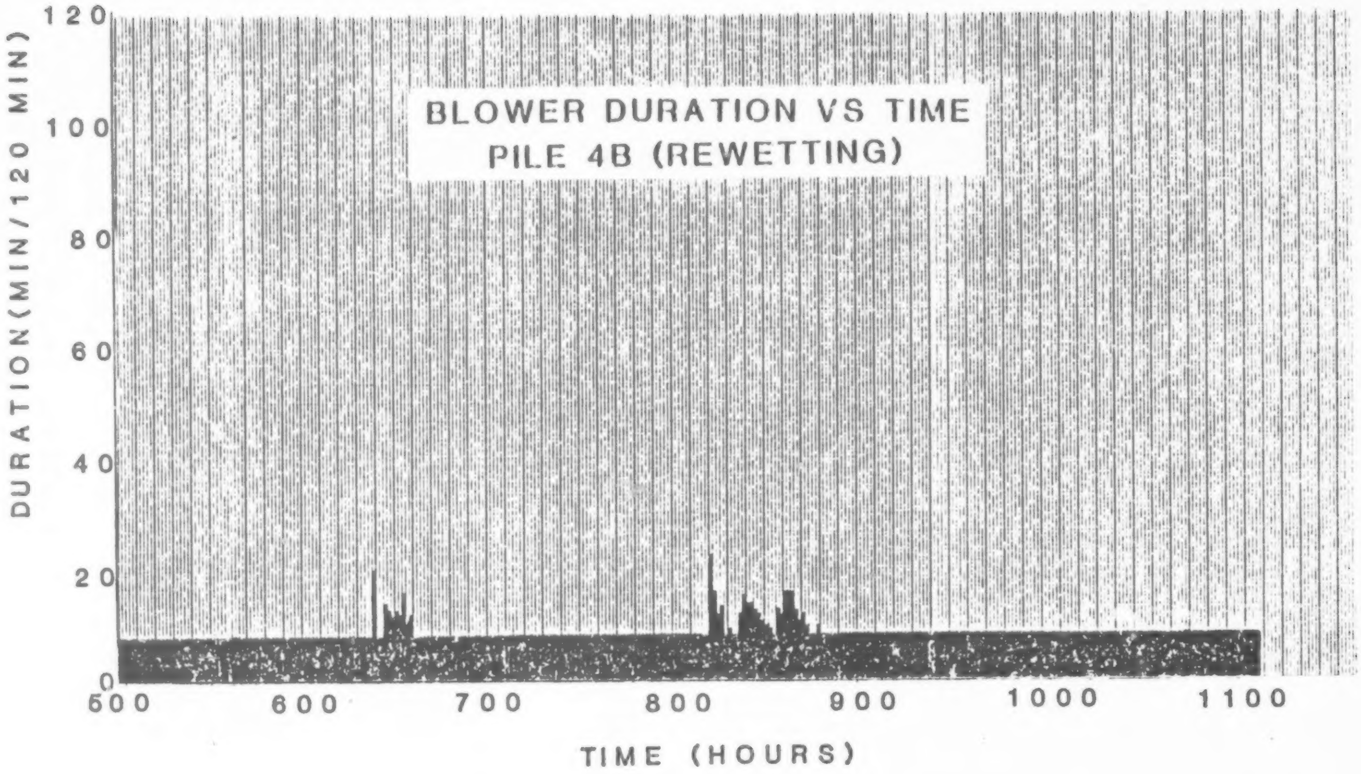

BLOWER DURATION VS TIME
PILE 4B (REWETTING)
DURATION(MIN/120 MIN)
120
100
80
60
40
20
0
500
600
700
800
900
1000
1100
TIME (HOURS)

FIG 99

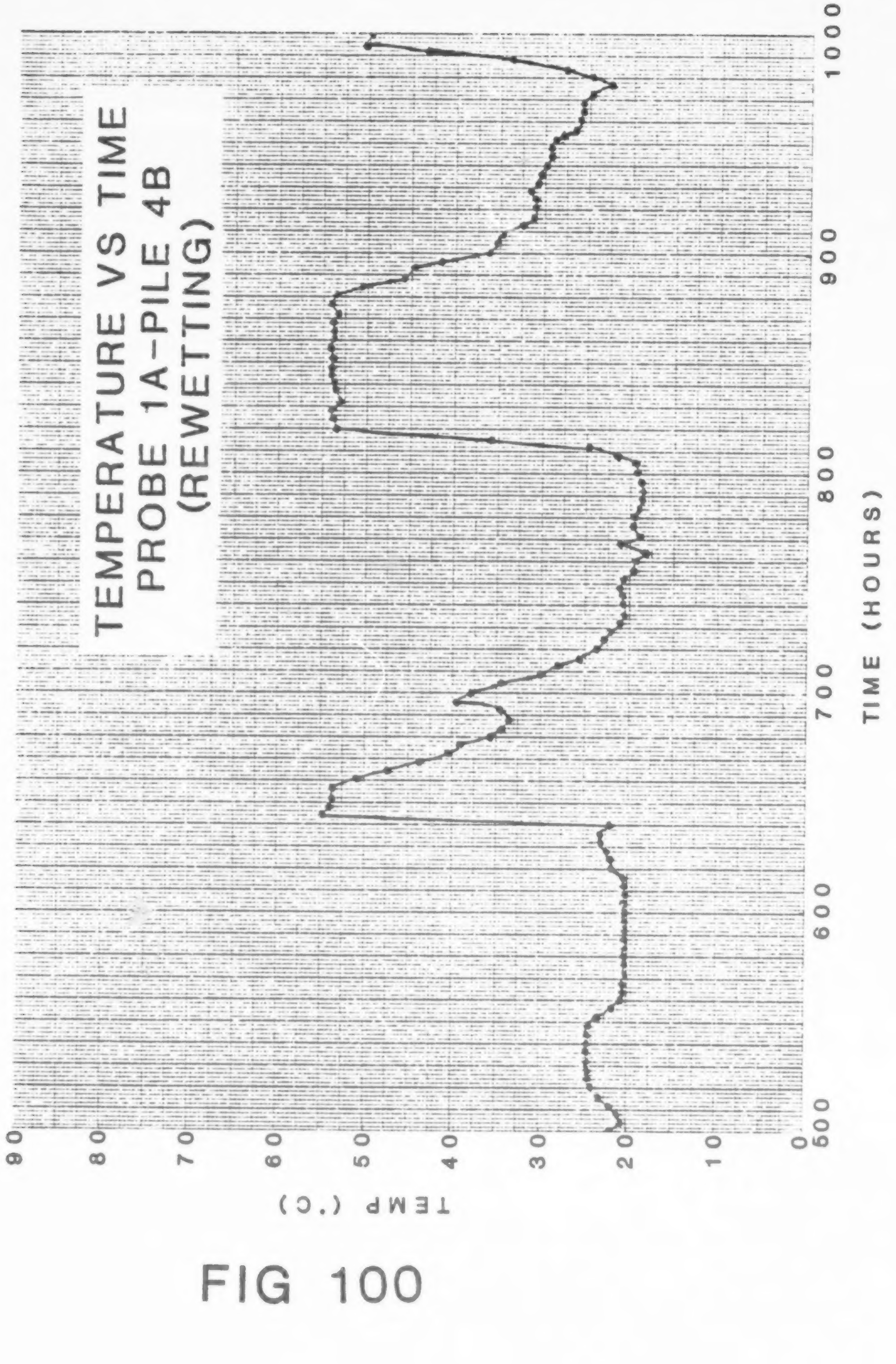

TEMPERATURE VS TIME
PROBE 1A-PILE 4B
(REWETTING)
TEMP (°C)
0
10
20
30
40
50
60
70
80
90
TIME (HOURS)
500
600
700
800
900
1000

FIG 100

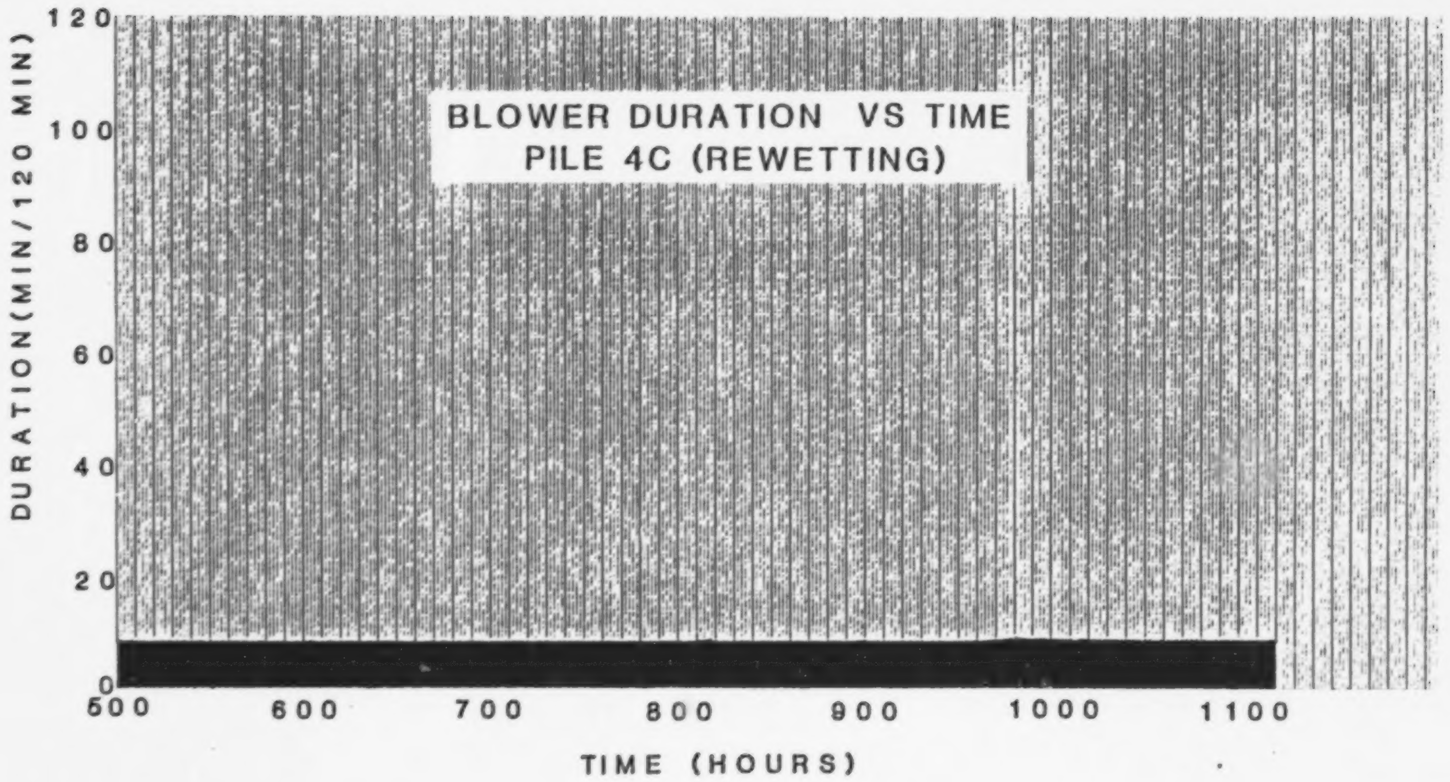

BLOWER DURATION VS TIME
PILE 4C (REWETTING)
DURATION(MIN/120 MIN)
0
20
40
60
80
100
120
500
600
700
800
900
1000
1100
TIME (HOURS)

FIG 101

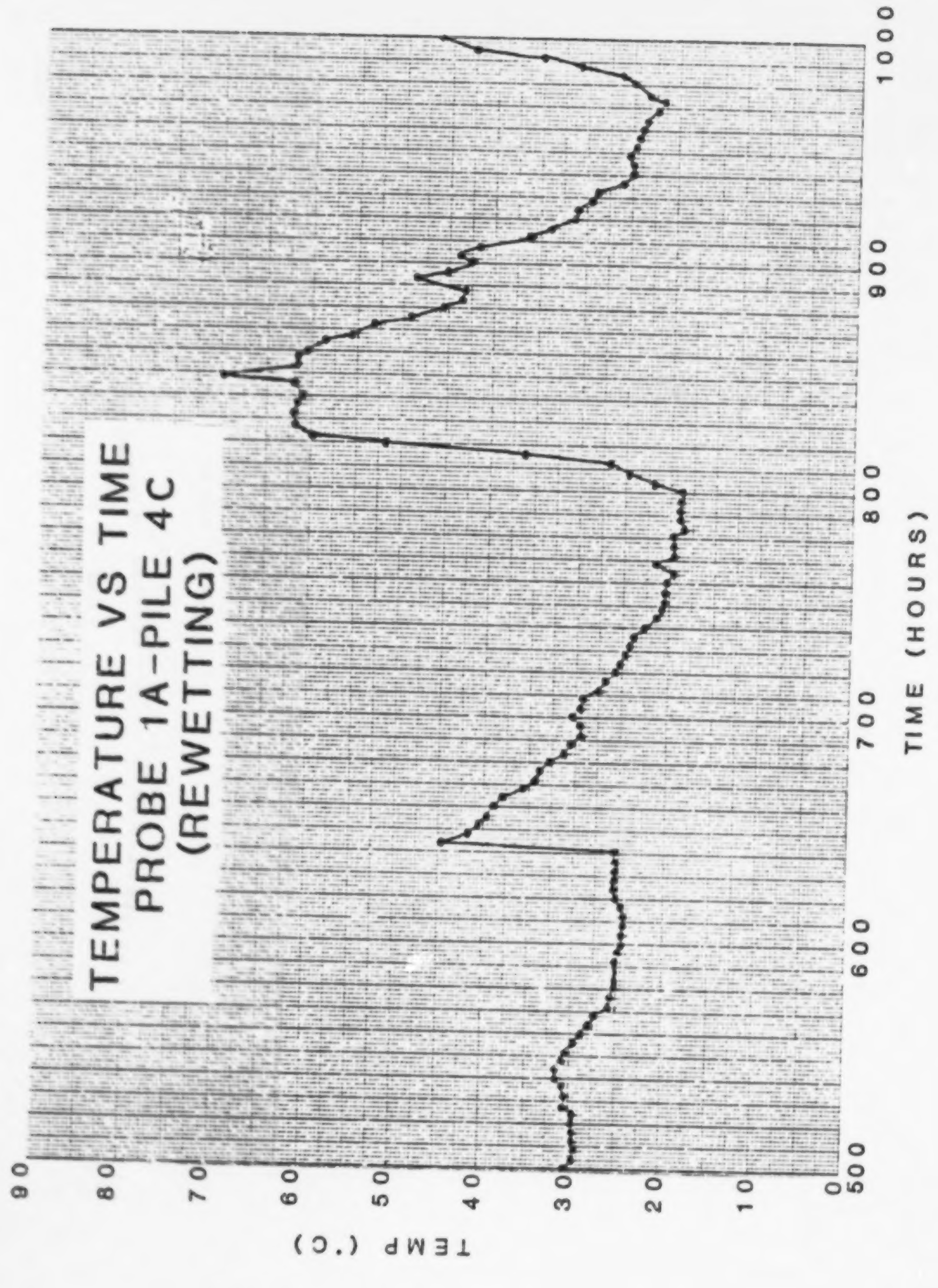

TEMPERATURE VS TIME
PROBE 1A-PILE 4C
(REWETTING)
TEMP (°C)
0
10
20
30
40
50
60
70
80
90
TIME (HOURS)
500
600
700
800
900
1000

FIG 102

RUN #5 LONGITUDINAL CROSS SECTION

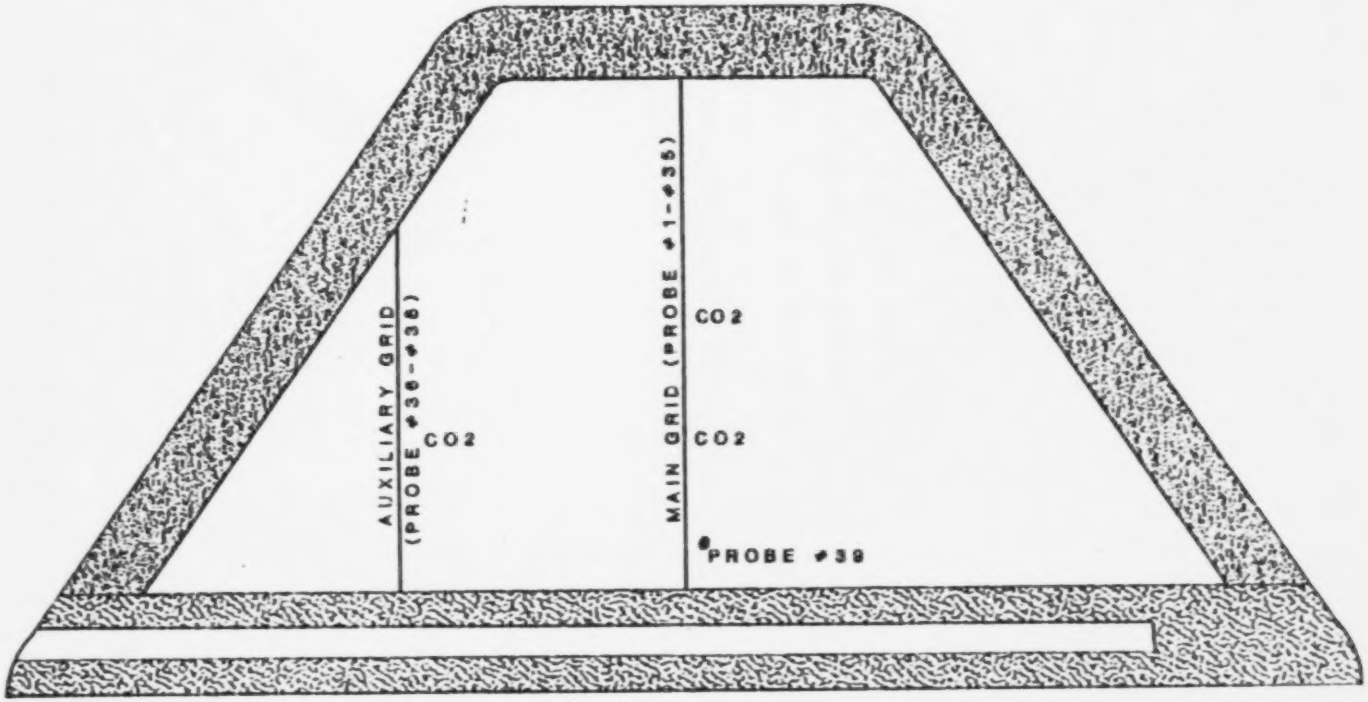
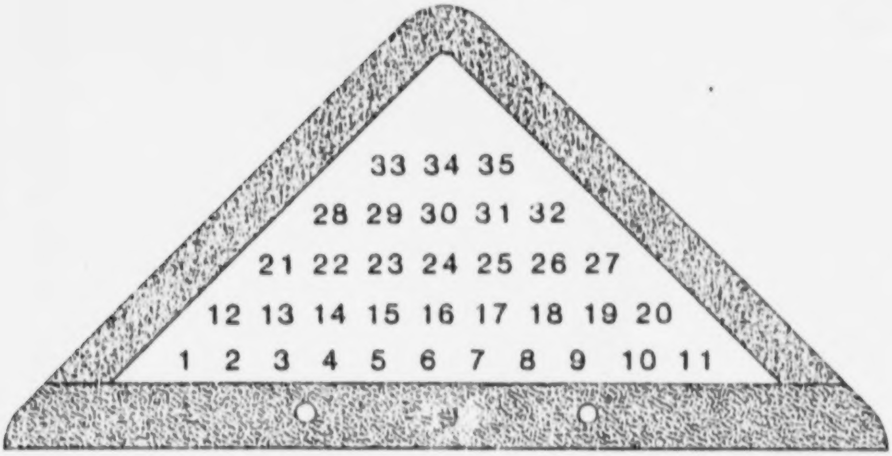

AUXILIARY GRID (PROBE #36-#38)
CO2
MAIN GRID (PROBE #1-#35)
CO2
CO2
PROBE #39

FIGURE 103

RUN #5 CENTER CROSS SECTIONS

Main Cross Section


33 34 35
28 29 30 31 32
21 22 23 24 25 26 27
12 13 14 15 16 17 18 19 20
1 2 3 4 5 6 7 8 9 10 11

Auxiliary Cross Section

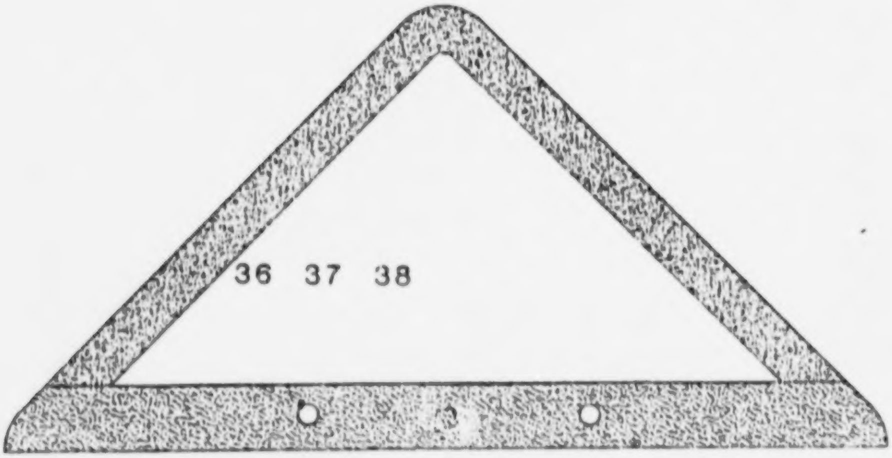


FIGURE 104

BLOWER DURATION
VS TIME RUN 5

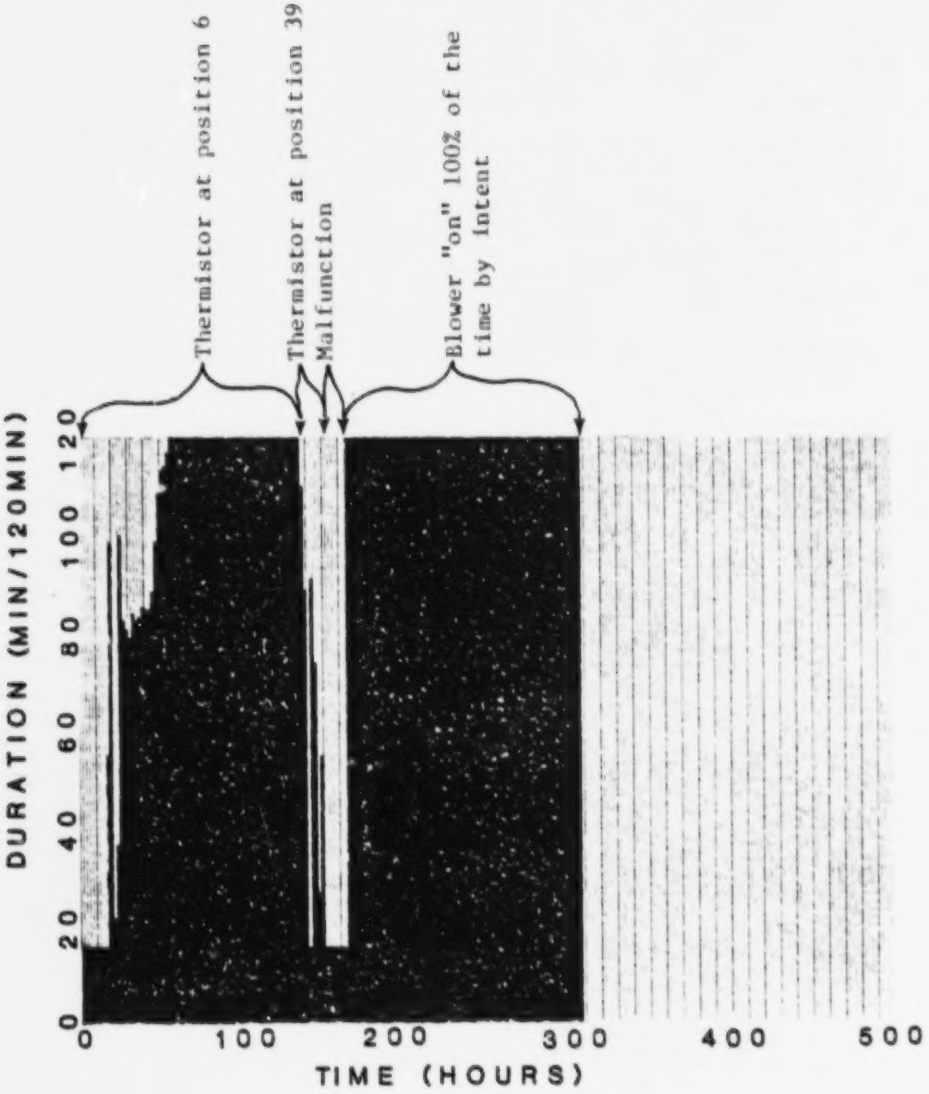
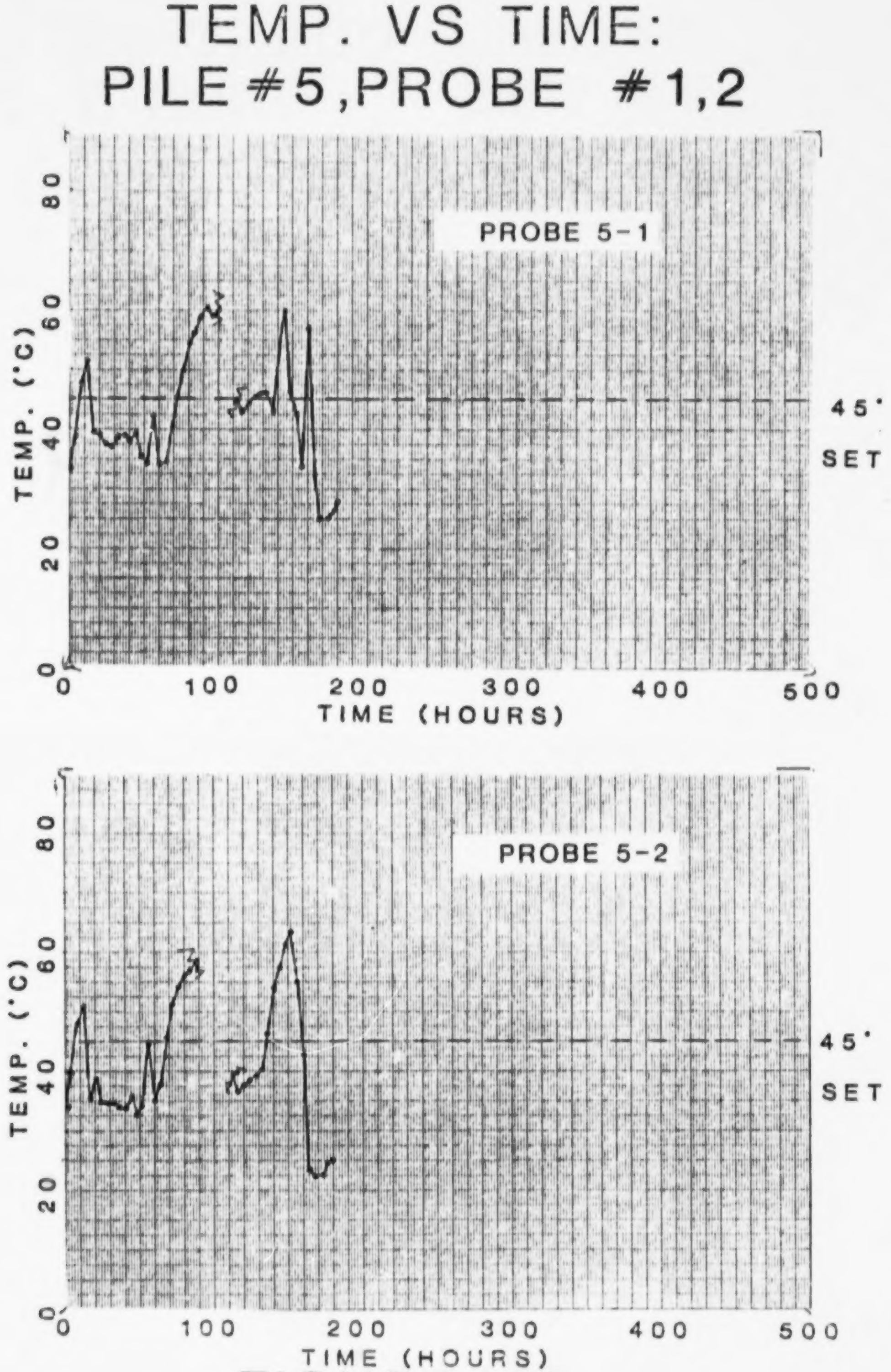


FIG 105



TEMP. VS TIME:
PILE #5,PROBE #1,2

FIGURE 106

TEMP. VS TIME: PILE #5, PROBE #3,4

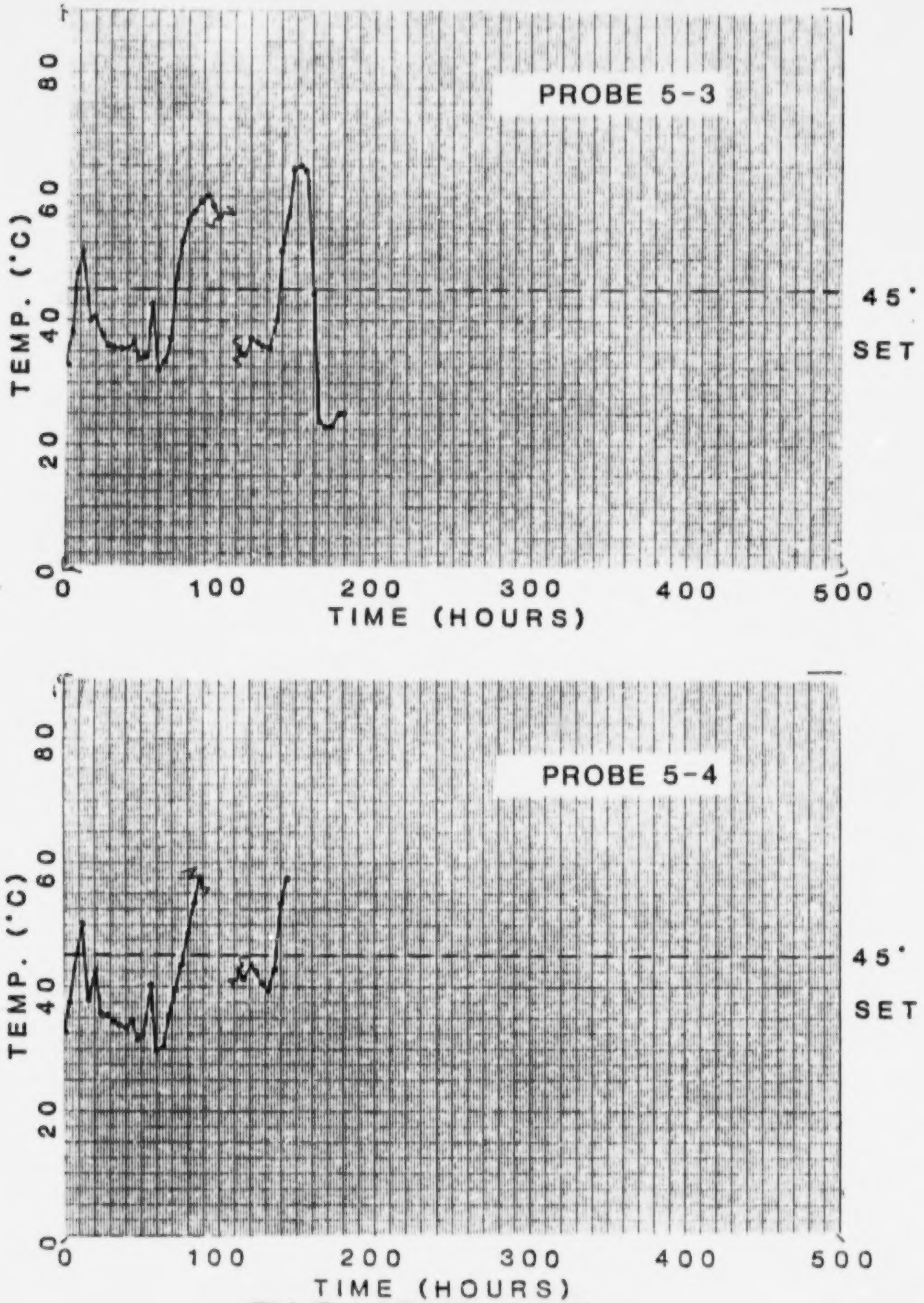
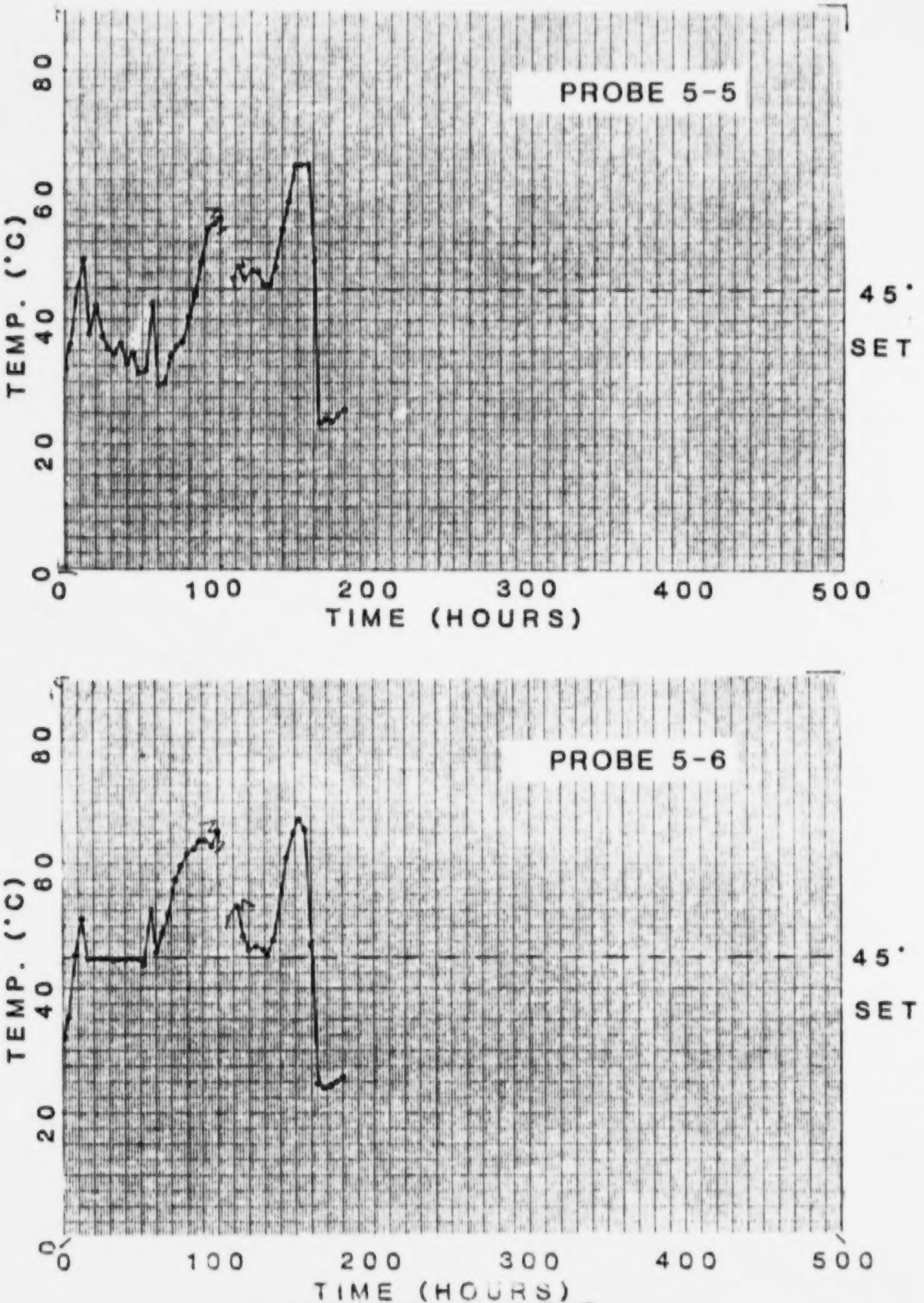


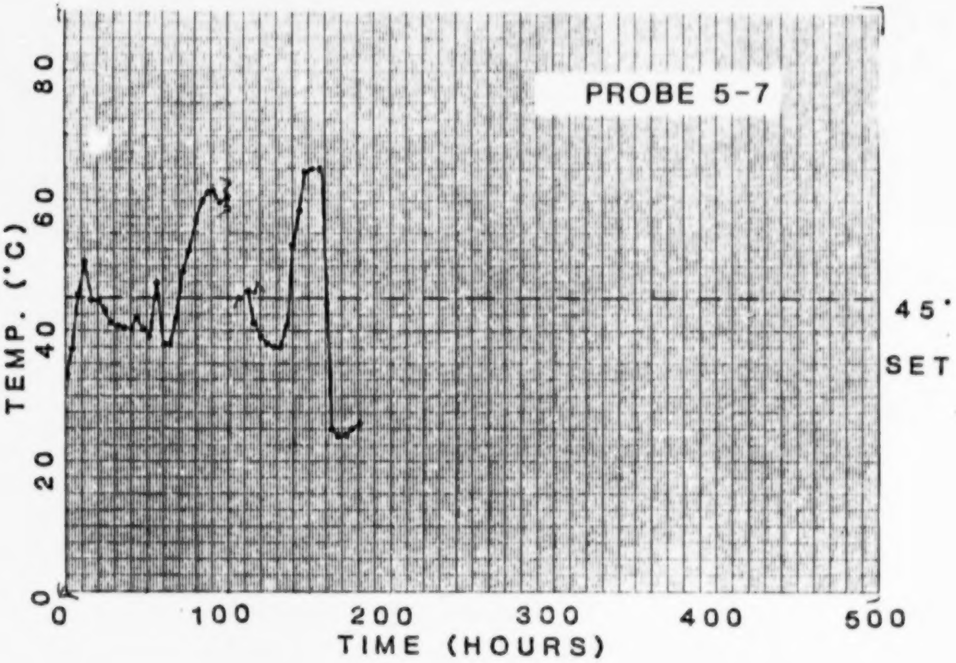
FIGURE 107



TEMP. VS TIME: PILE #5, PROBE #5,6

FIGURE 108

TEMP. VS TIME:
PILE #5,PROBE #7,8



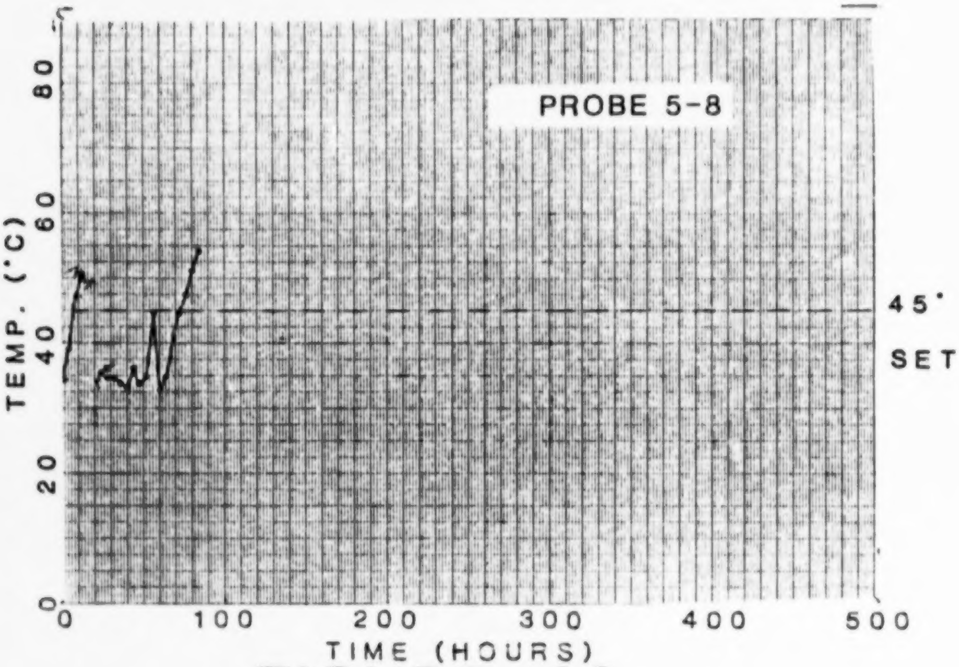


FIGURE 109

TEMP. VS TIME:
PILE #5,PROBE #9,10

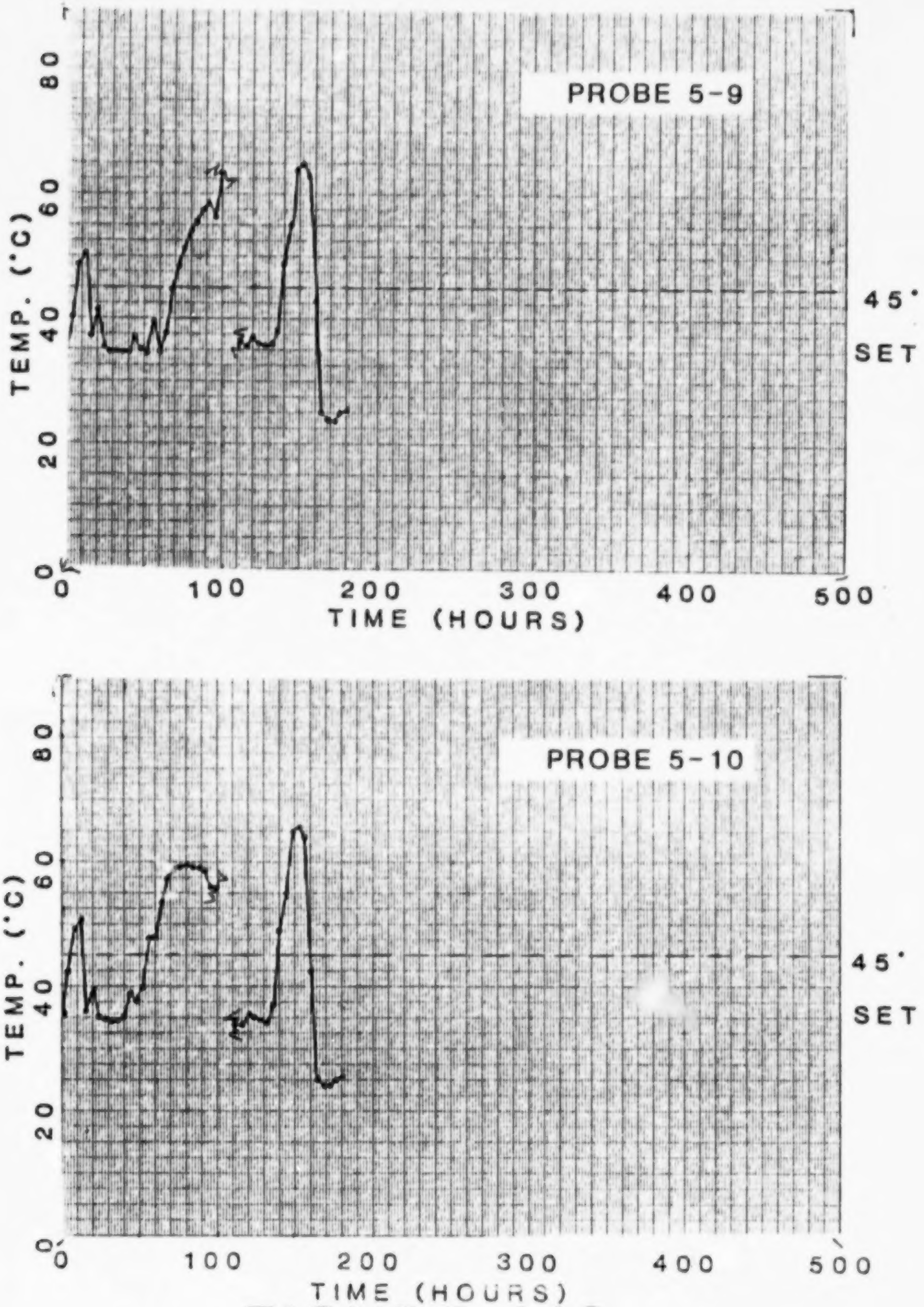


FIGURE 110

TEMP. VS TIME:
PILE #5, PROBE #11,12

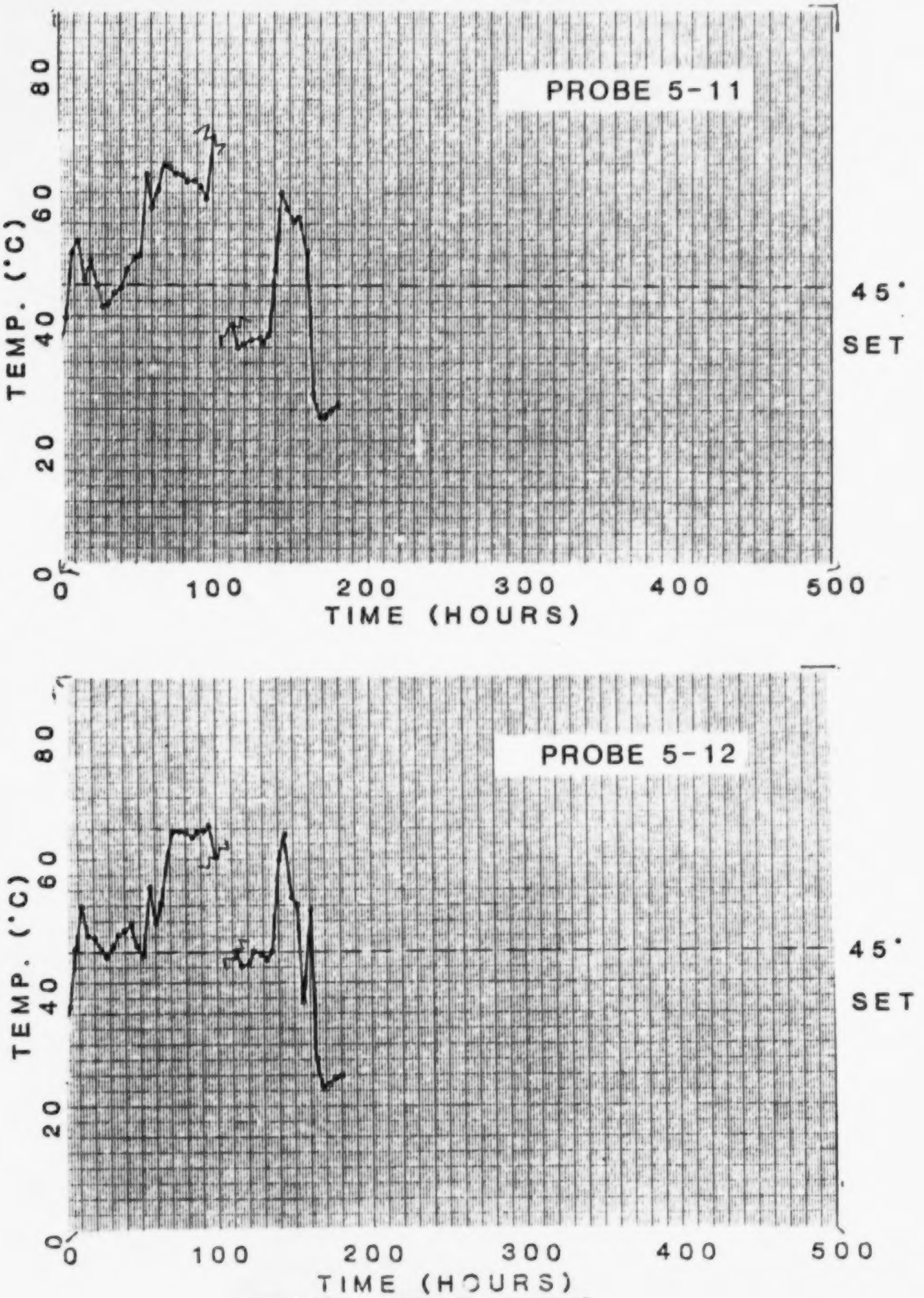


FIGURE 111

TEMP. VS TIME:
PILE #5, PROBE #13,14

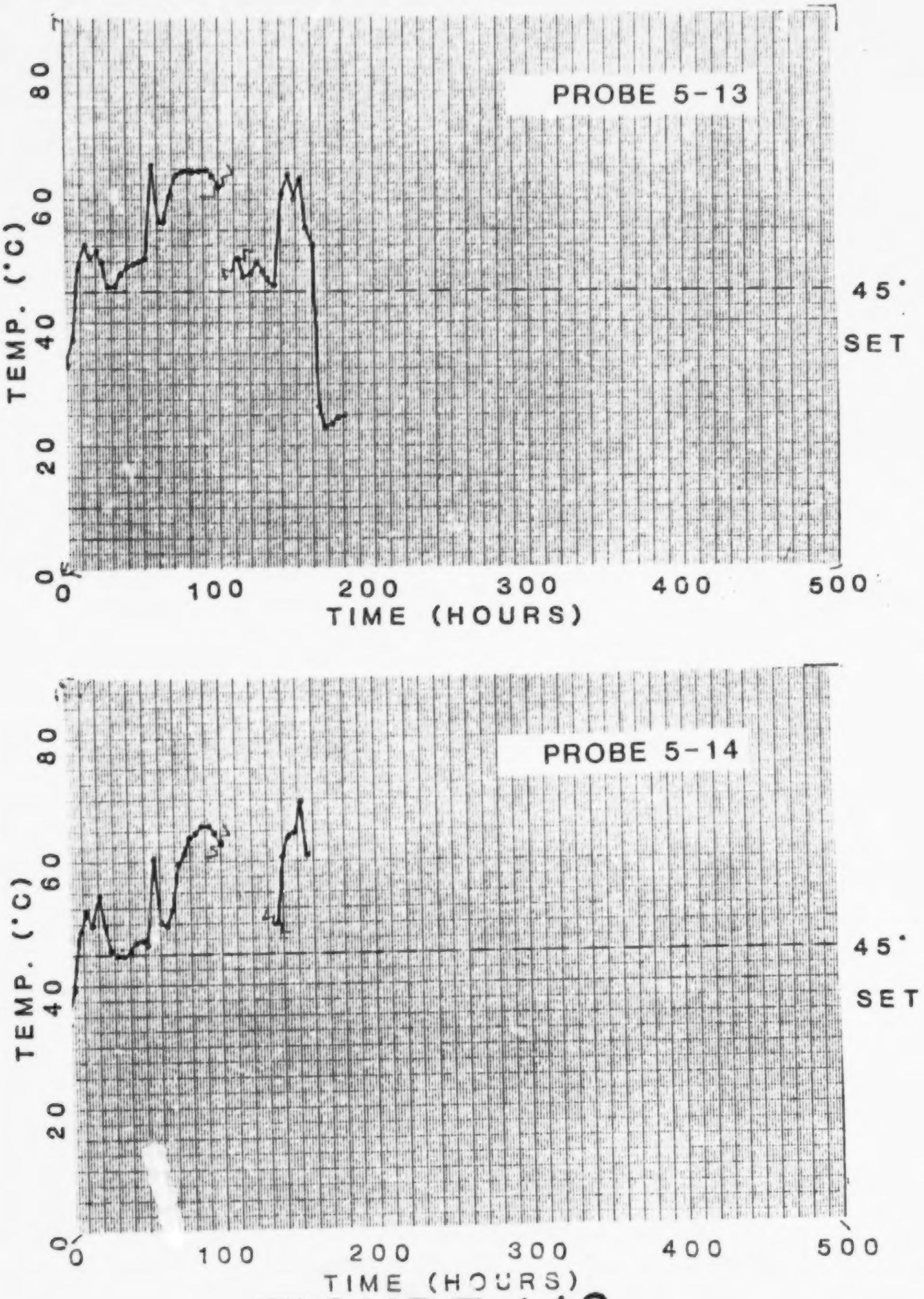


FIGURE 112

TEMP. VS TIME: PILE #5,PROBE #15,16

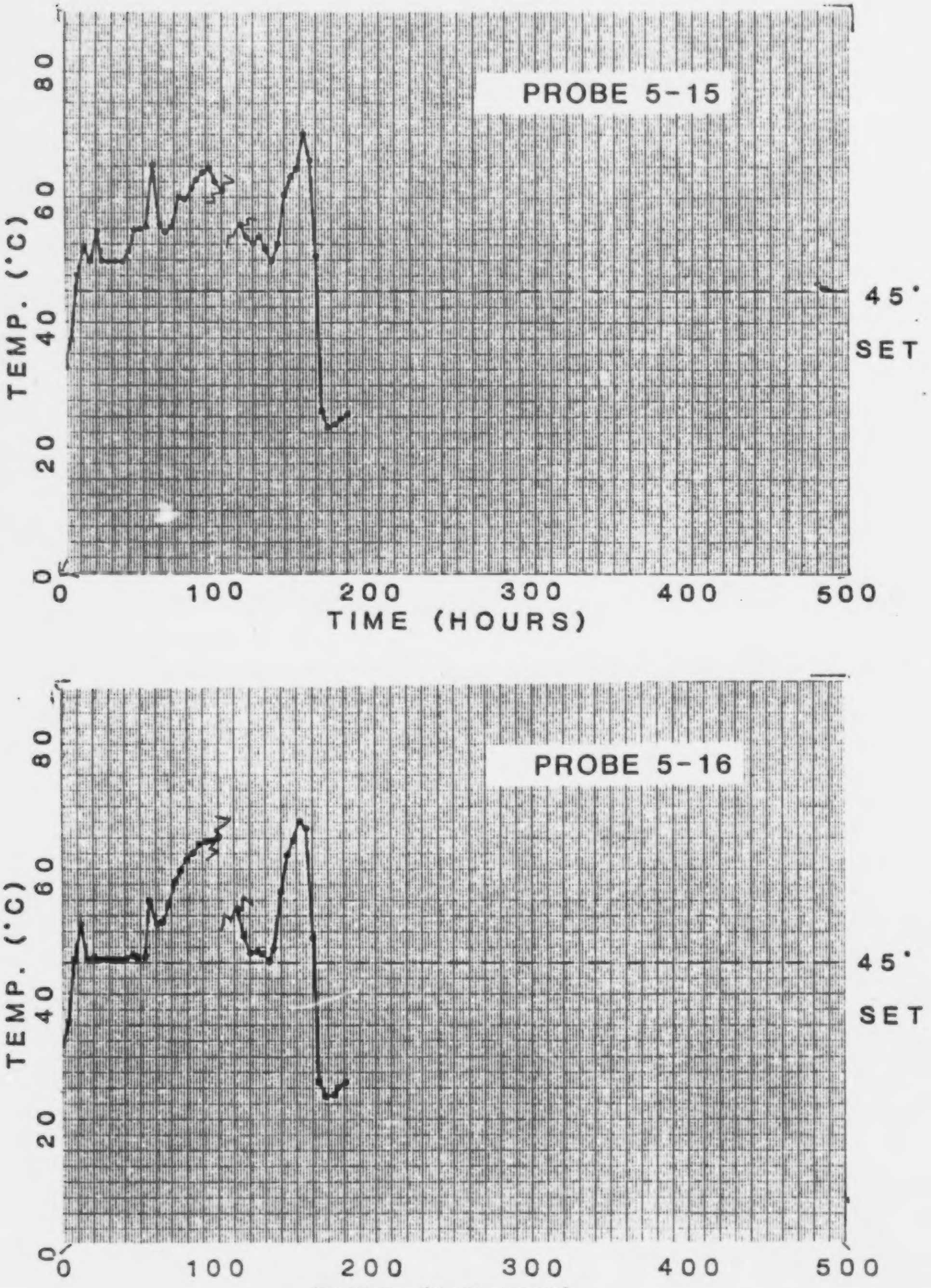


FIGURE 113

TEMP. VS TIME: PILE #5,PROBE #17,18

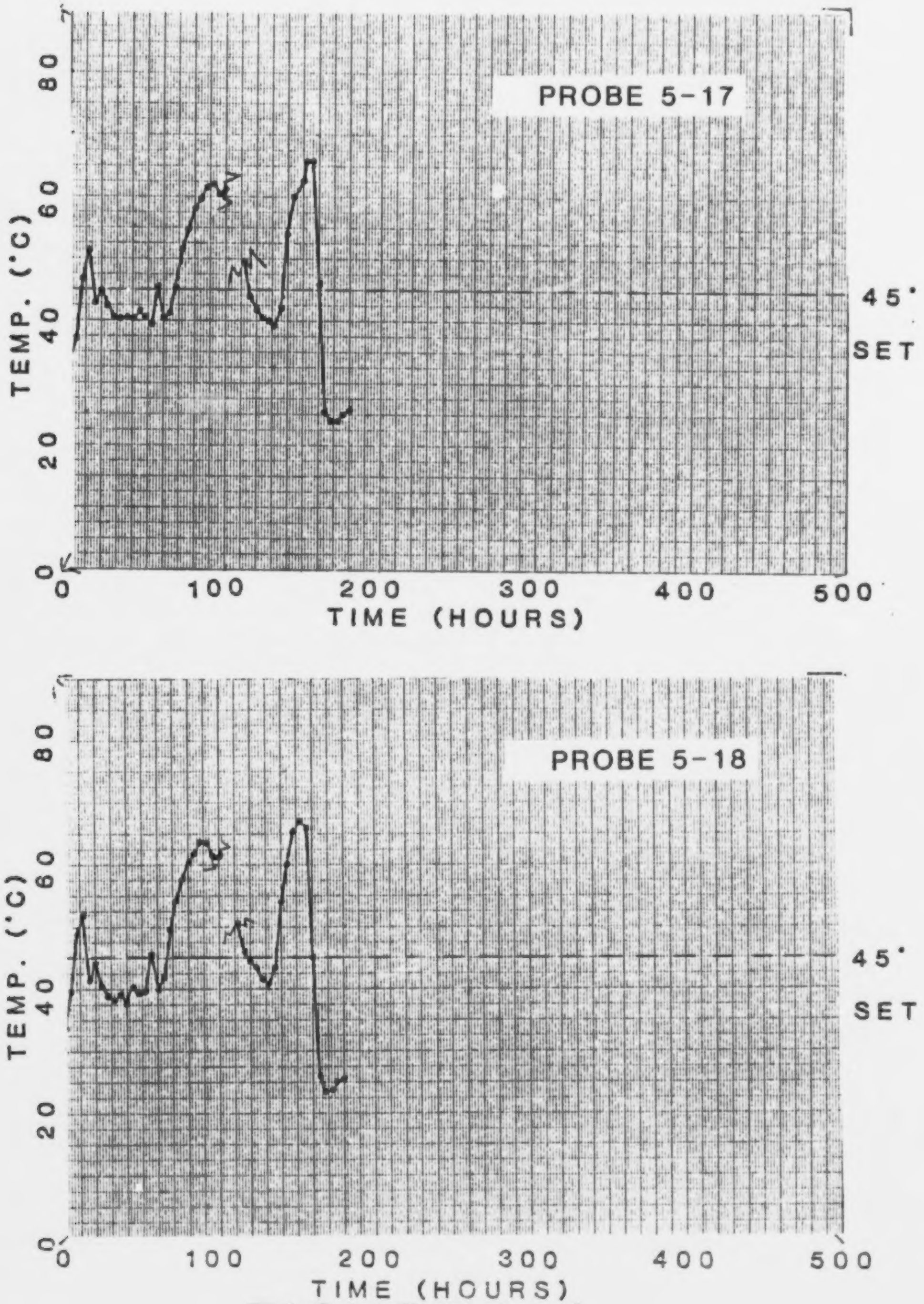


FIGURE 114

TEMP. VS TIME: PILE #5, PROBE #19,20

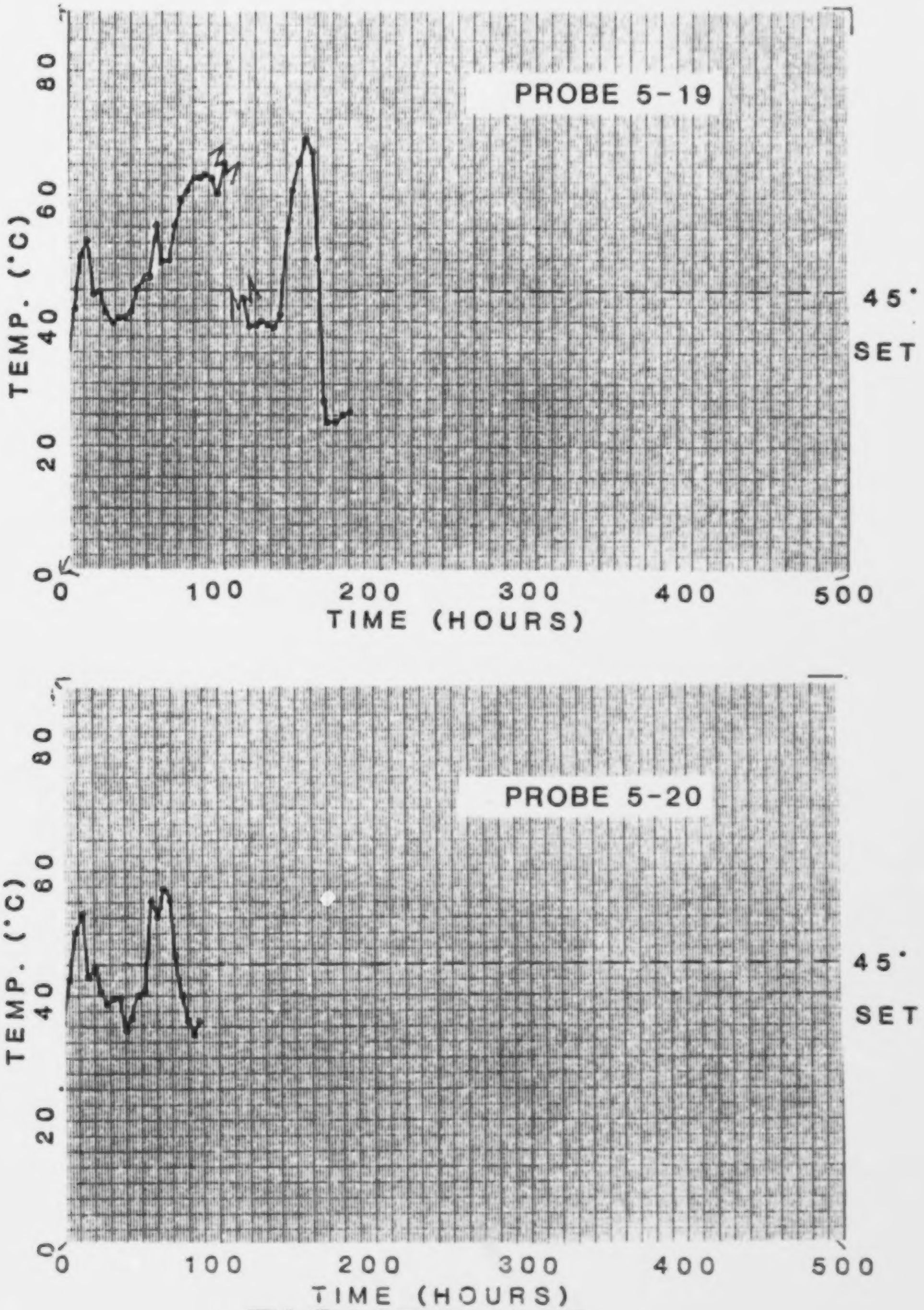


FIGURE 115

TEMP. VS TIME:
PILE #5,PROBE #21,22

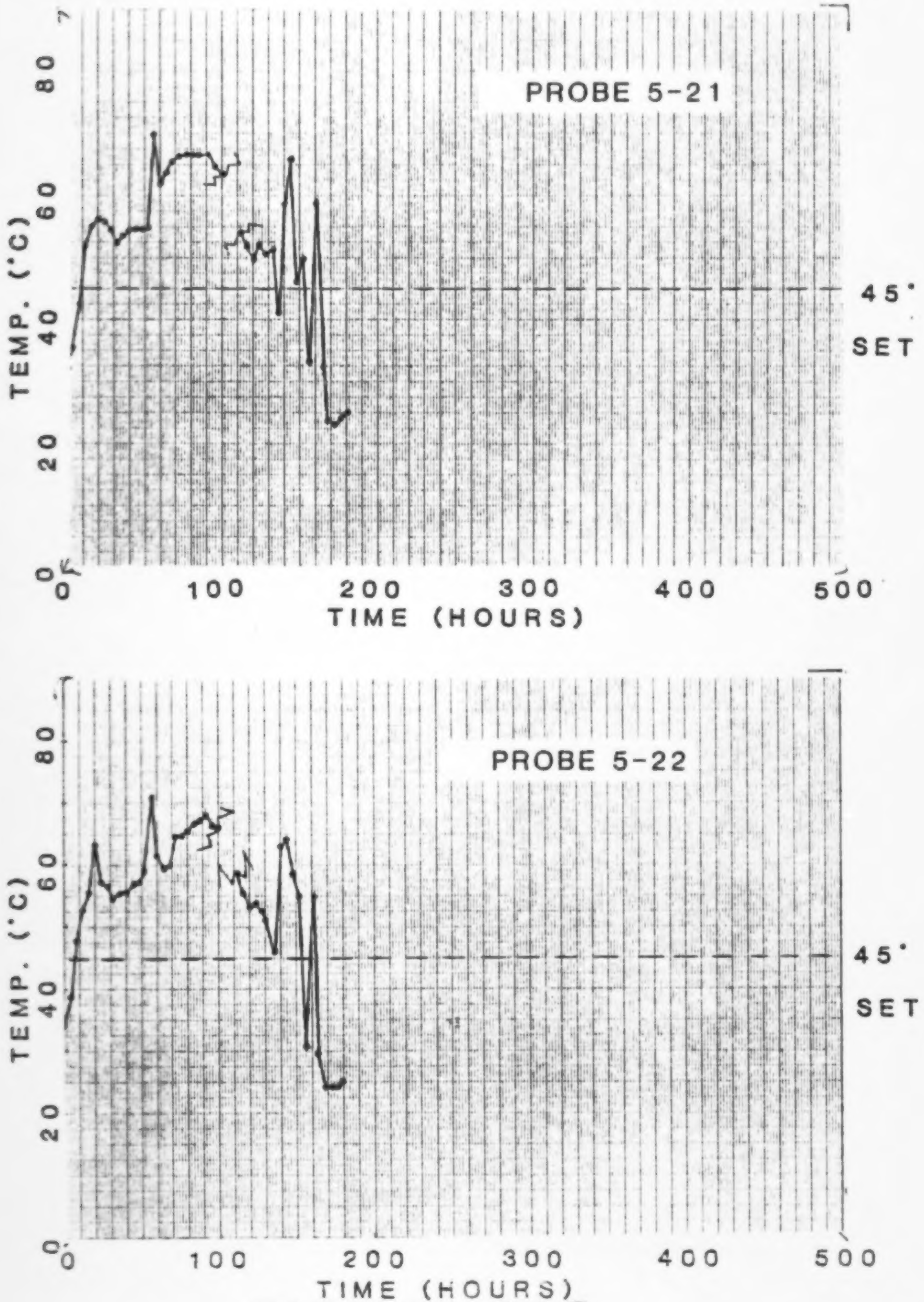
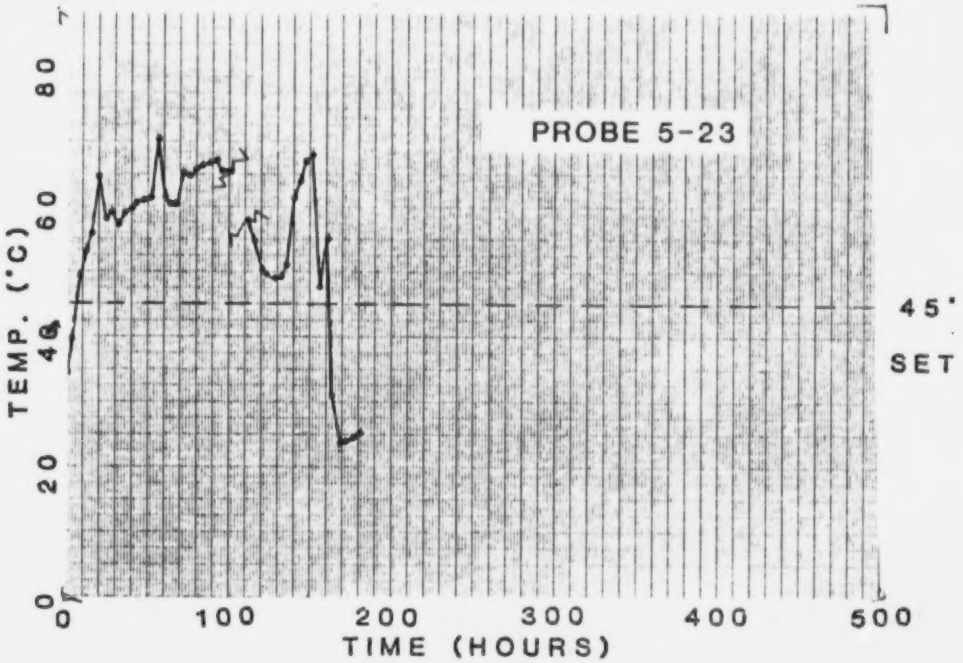


FIGURE 116

TEMP. VS TIME:
PILE #5, PROBE #23,25



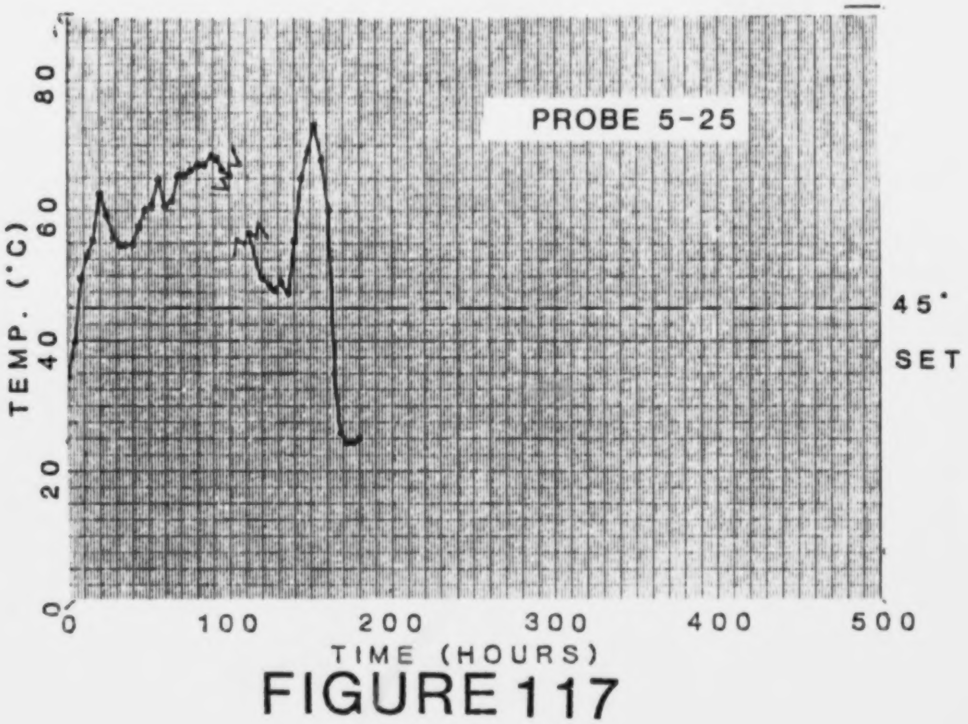
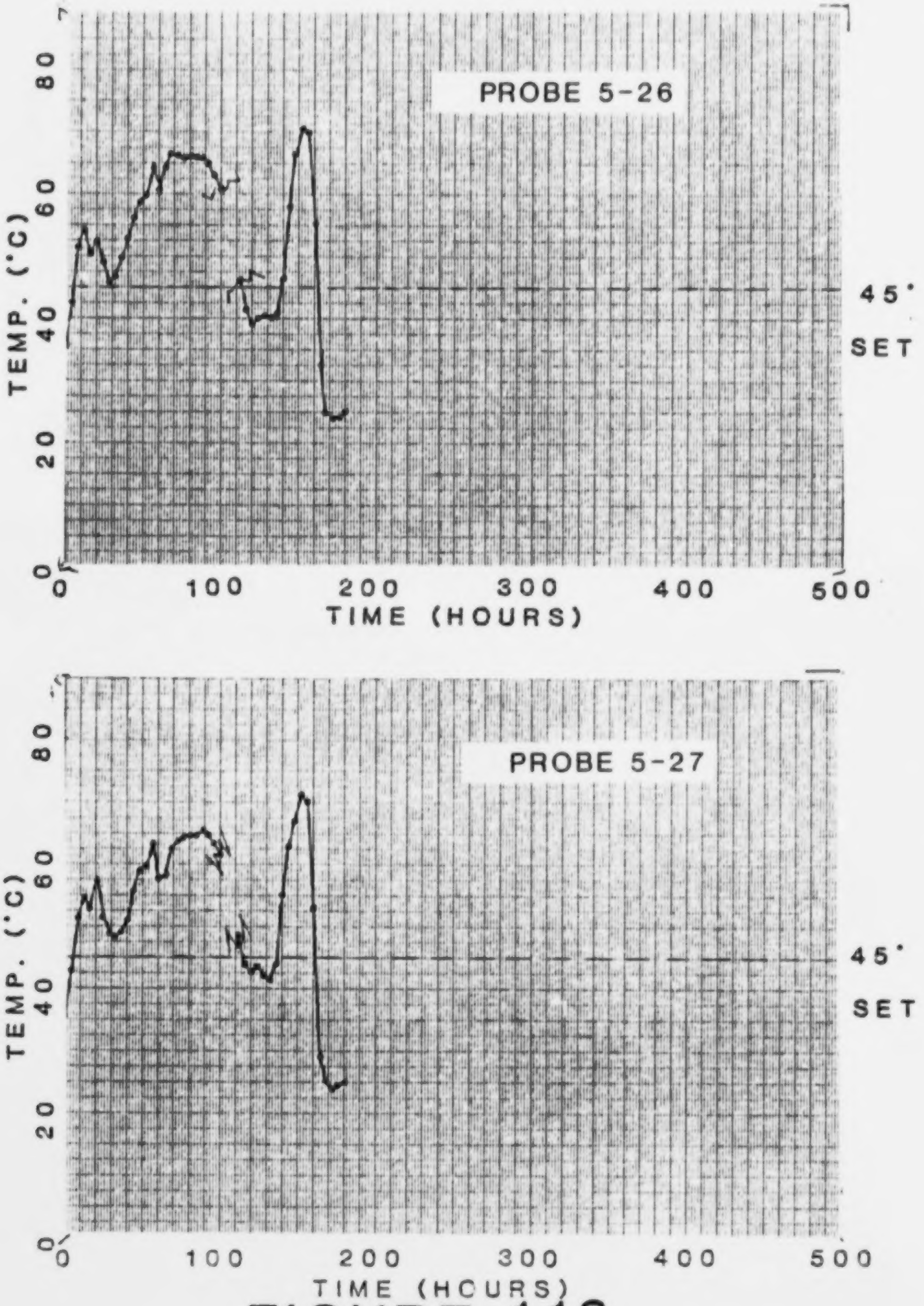


FIGURE 117



TEMP. VS TIME: PILE #5,PROBE #26,27

FIGURE 118

TEMP. VS TIME:
PILE #5,PROBE #28,29

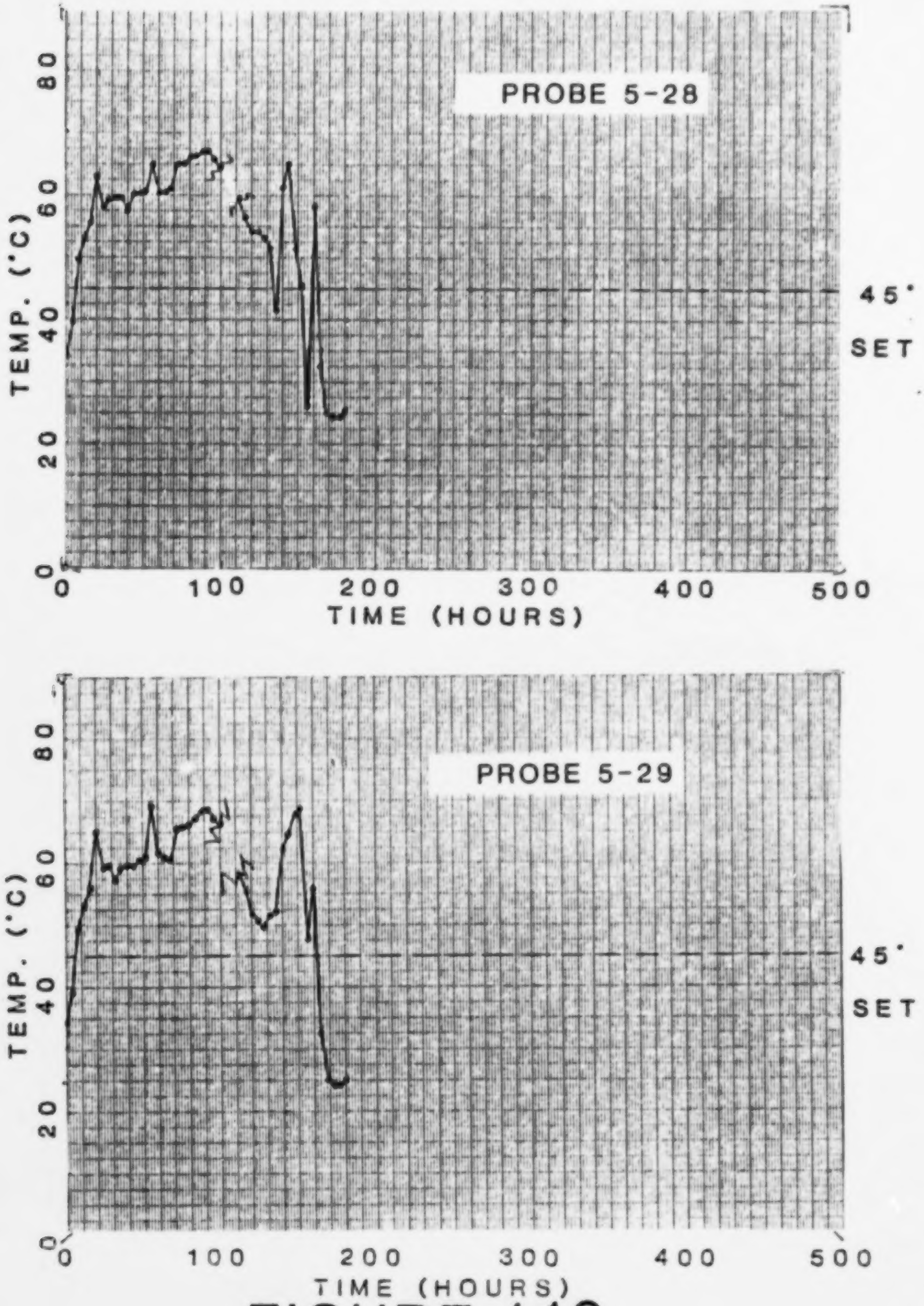


FIGURE 119

TEMP. VS TIME:
PILE #5,PROBE #30,31

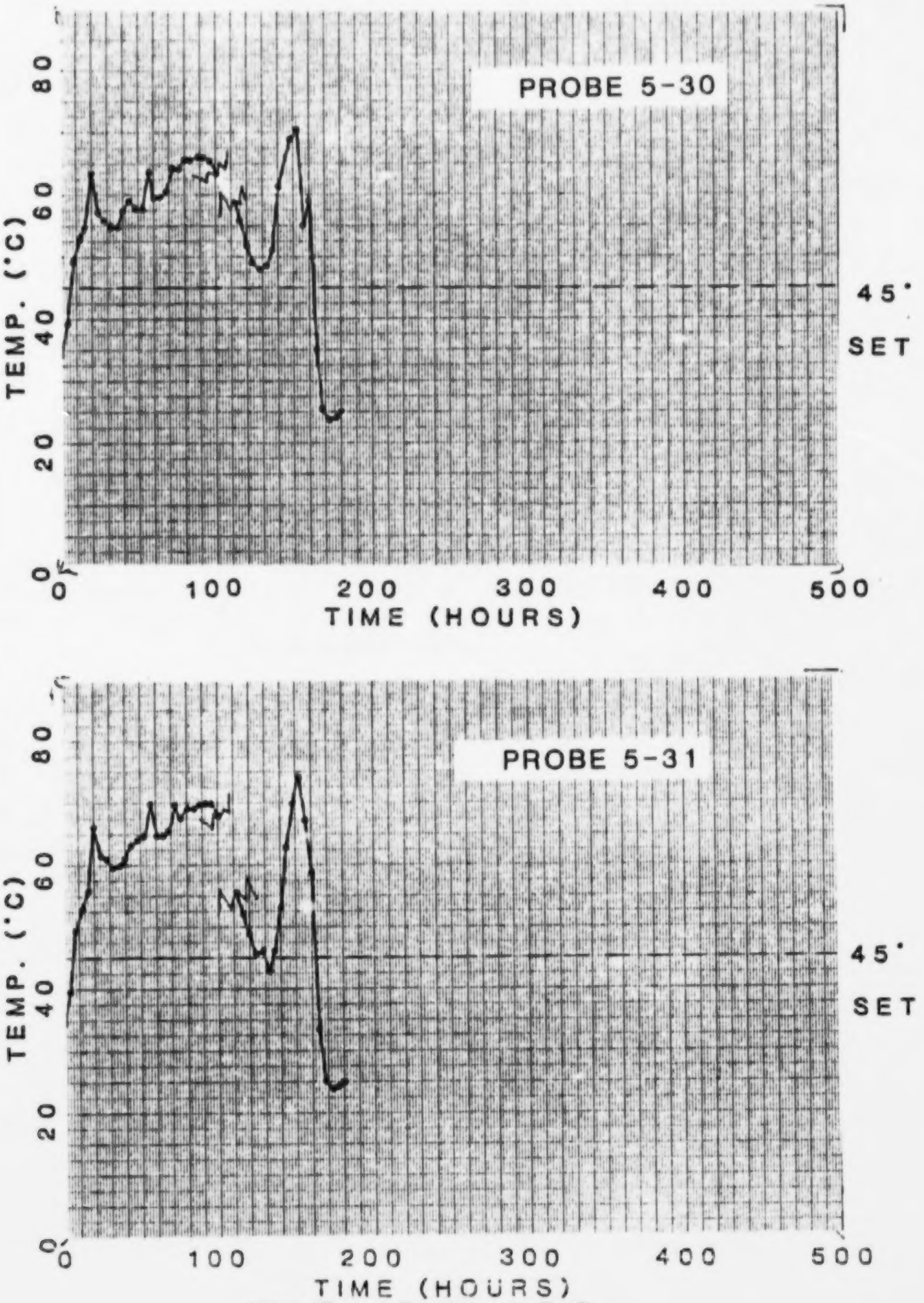


FIGURE 120

TEMP. VS TIME:
PILE #5,PROBE #32,33

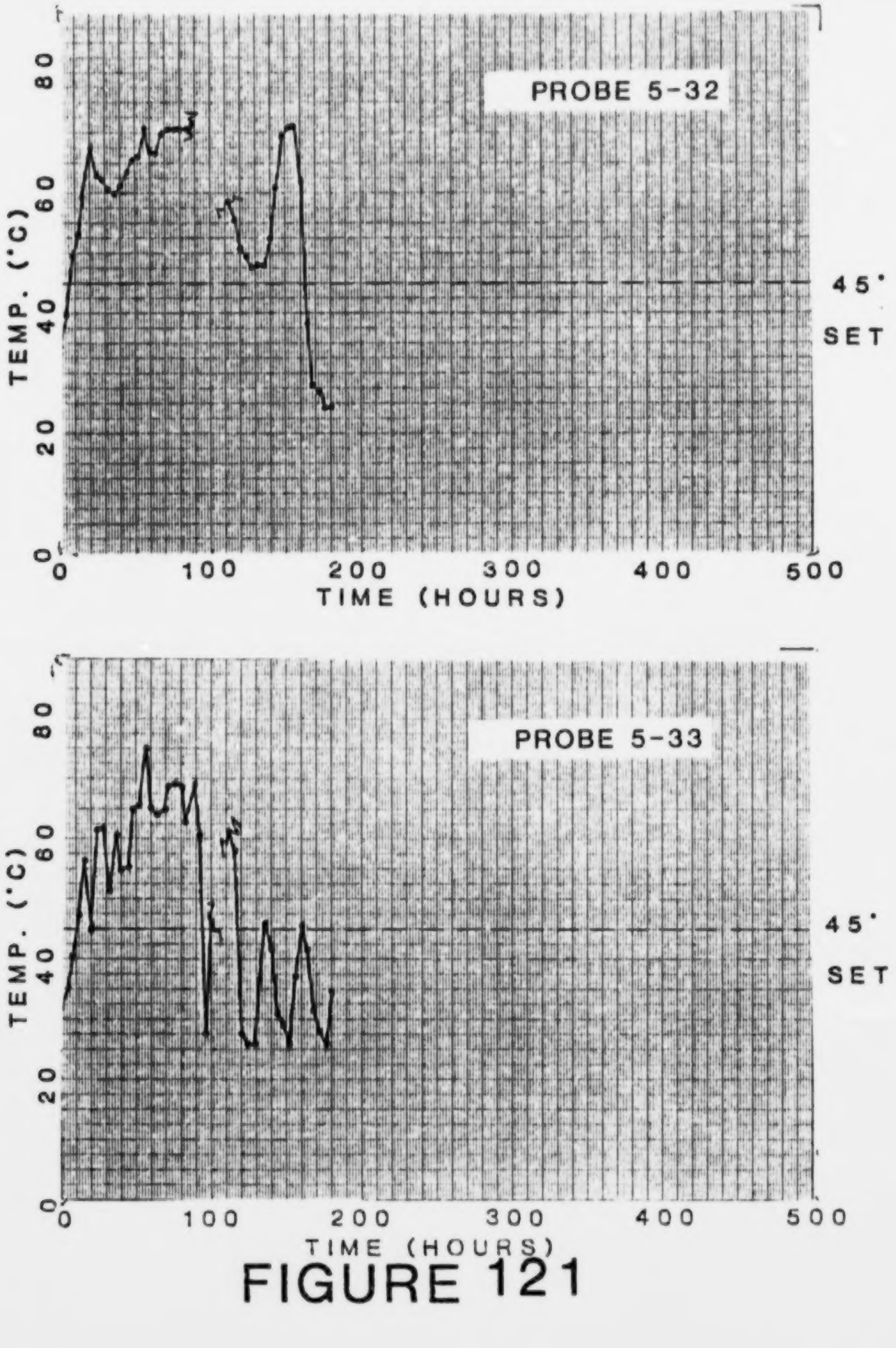


FIGURE 121

TEMP. VS TIME: PILE #5, PROBE #34,36

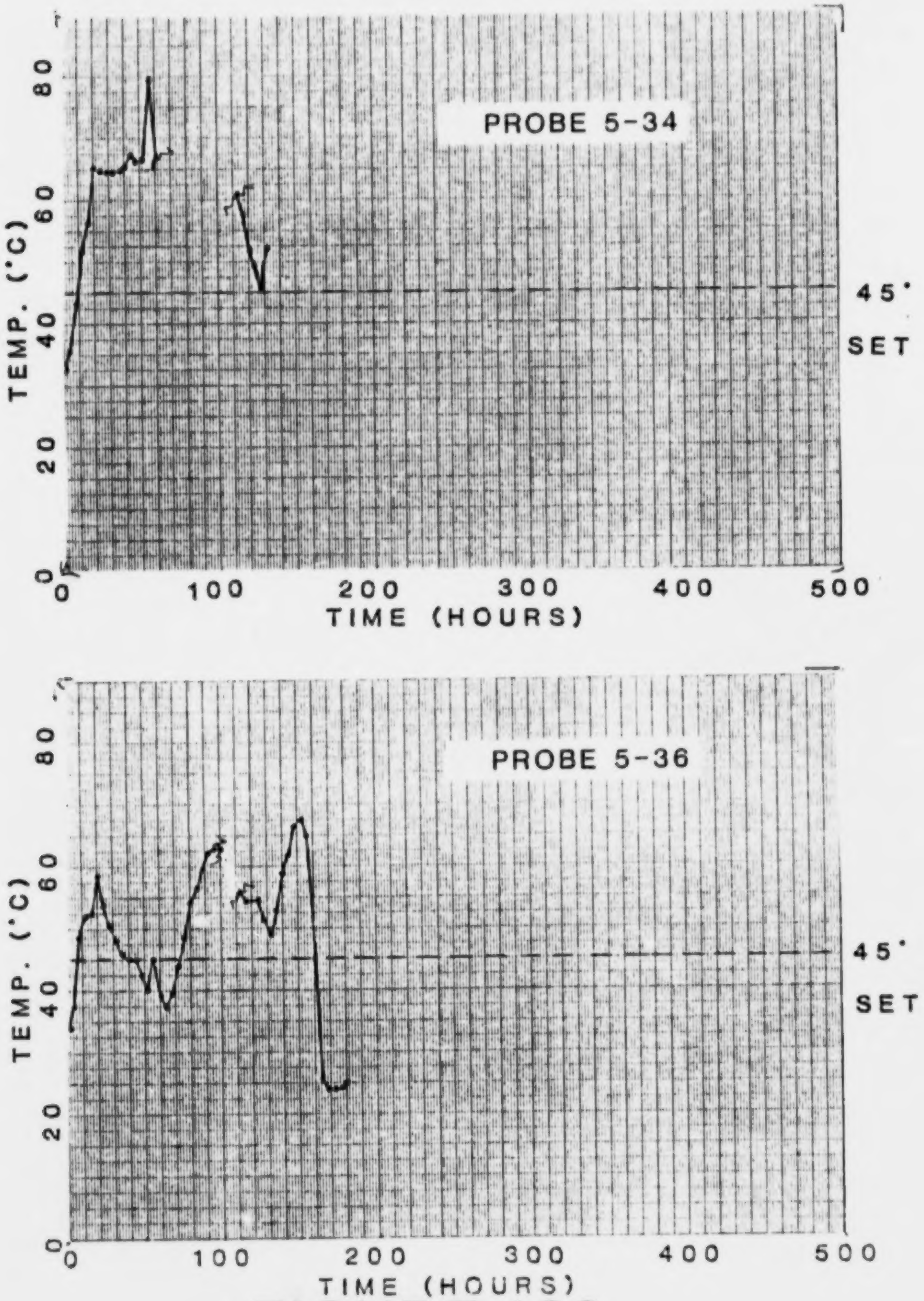


FIGURE 122

TEMP. VS TIME:
PILE #5,PROBE #37,38

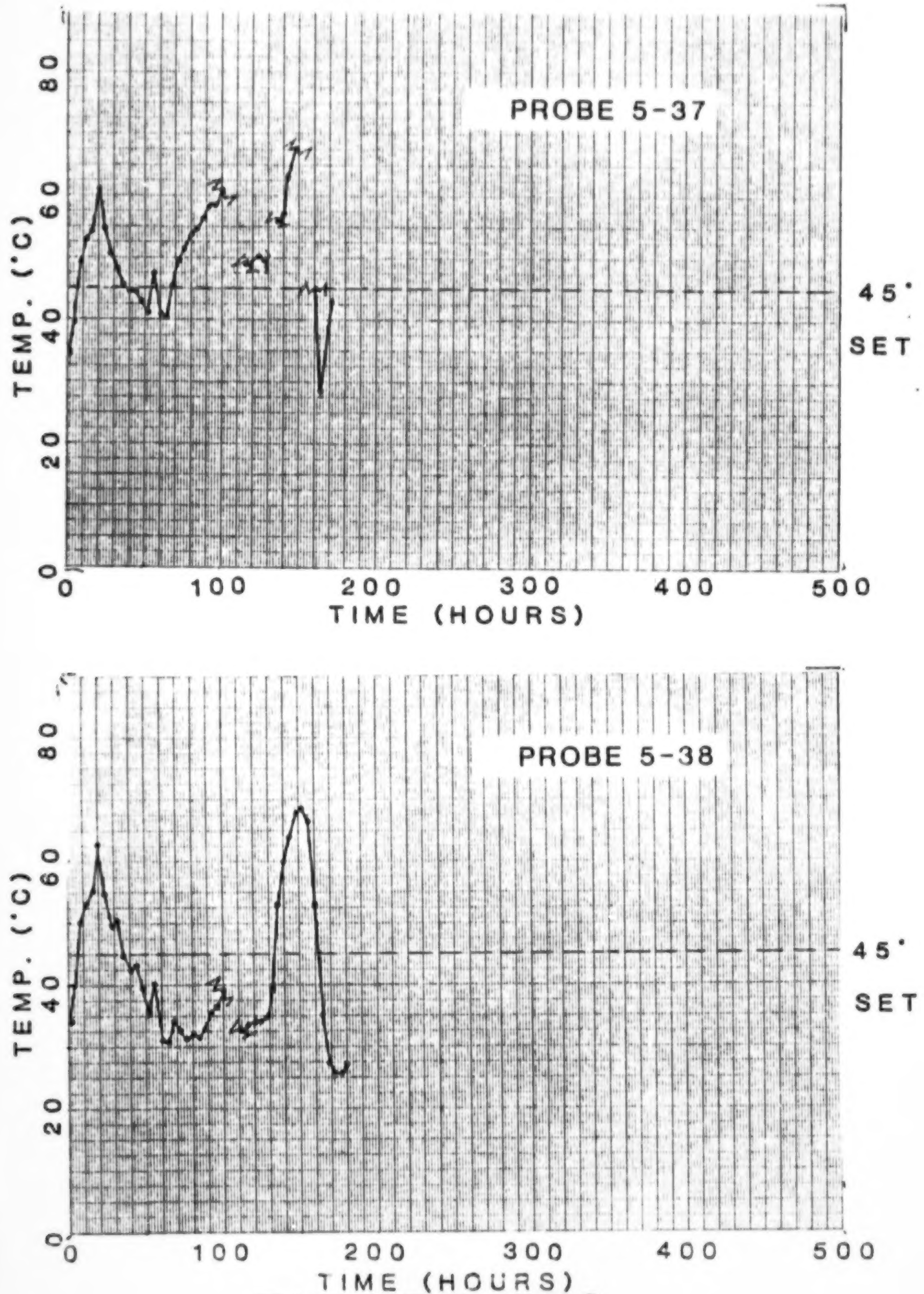


FIGURE 123

TEMP. VS TIME:
PILE #5,PROBE #39

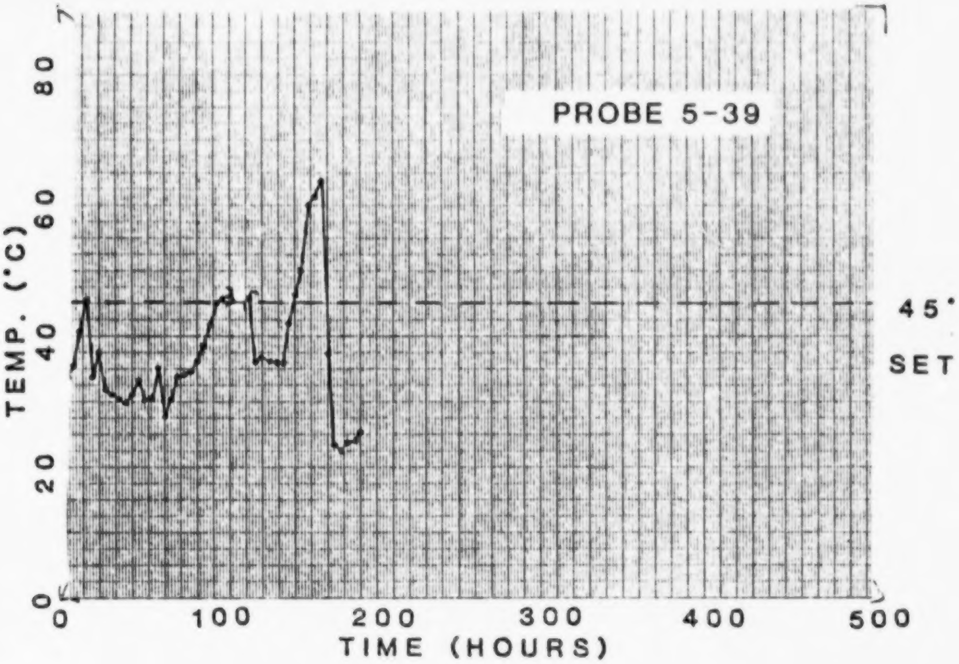


FIGURE 124

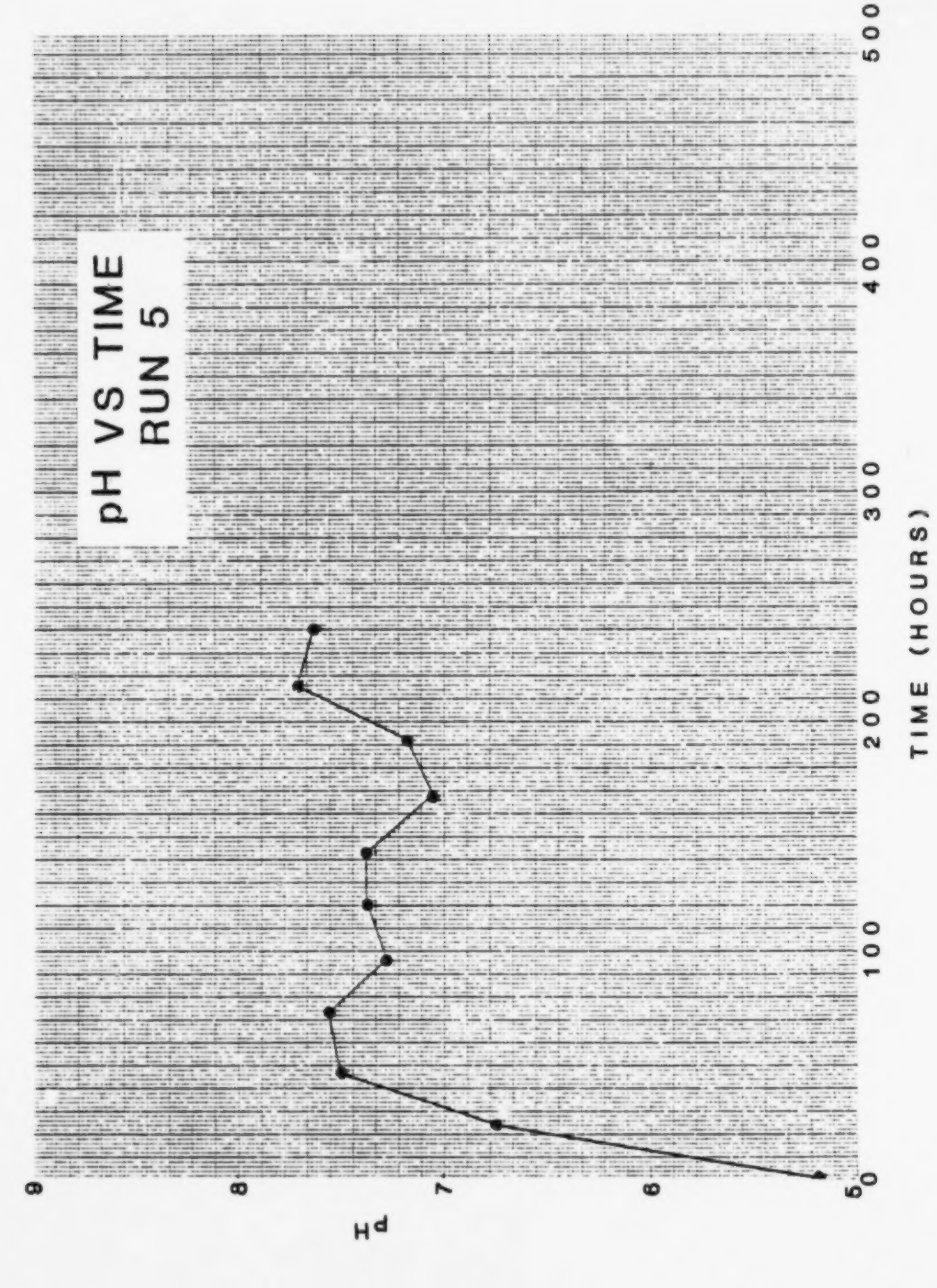
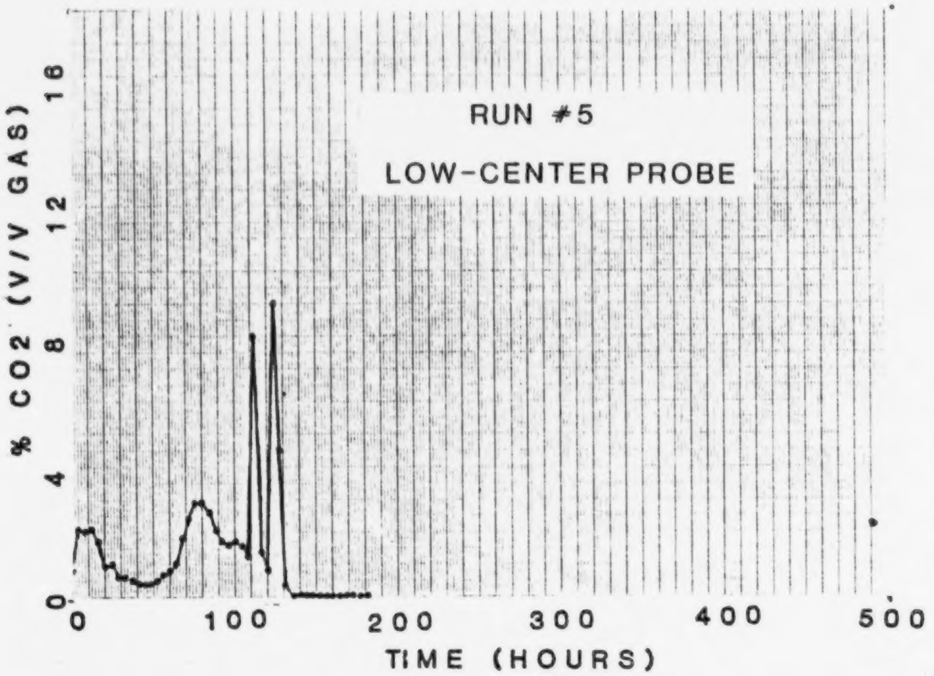


FIG 125

% CO2 VS TIME- RUN #5



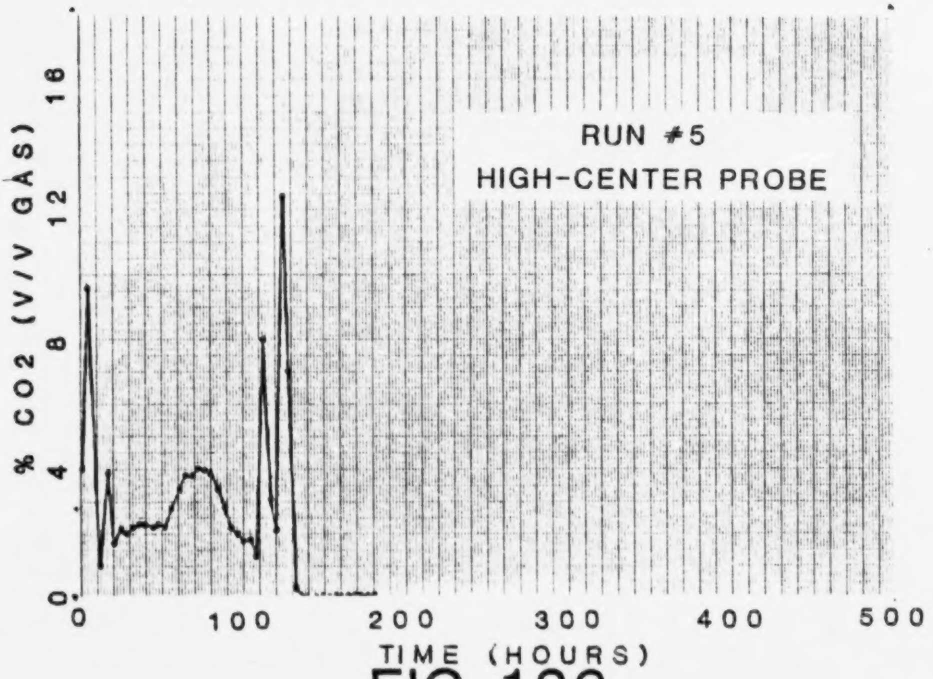
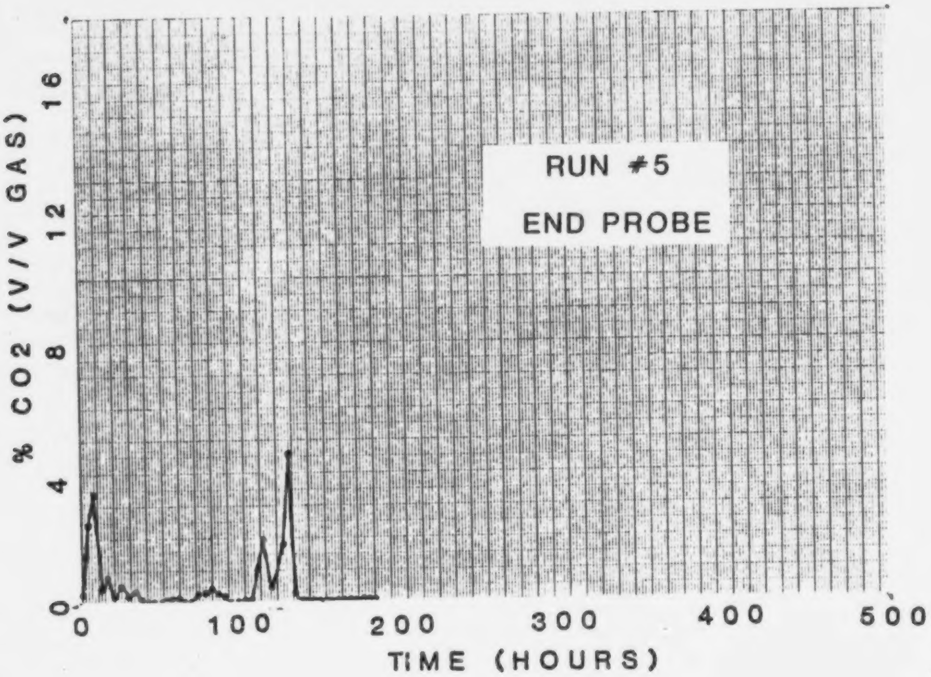


FIG 126



% CO2 VS TIME- RUN #5

FIG 127

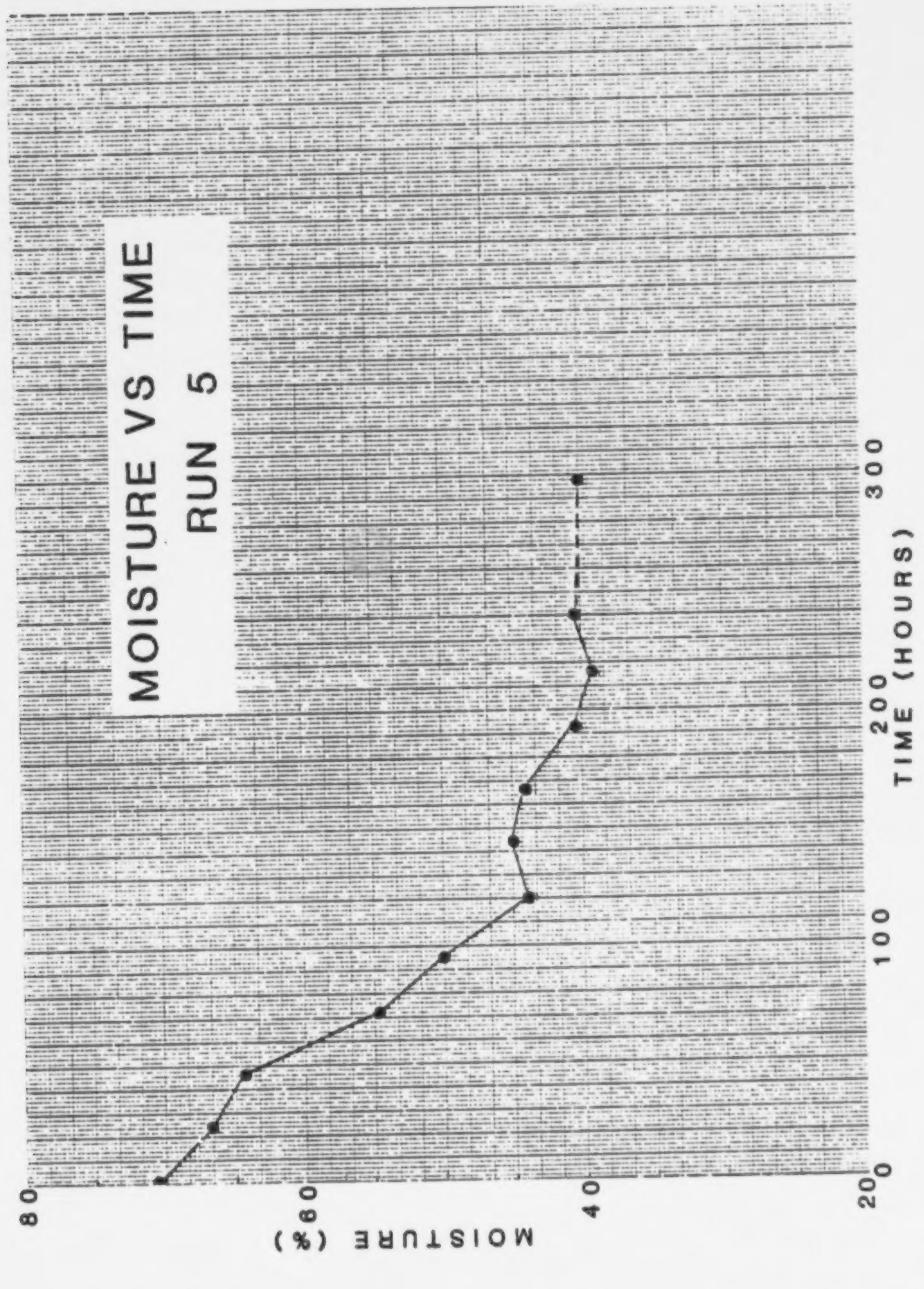

MOISTURE VS TIME
RUN 5
TIME (HOURS)
0
100
200
300
MOISTURE (%)
80
60
40
20

FIG 128

RATE OF HEAT OUTPUT VS TIME FOR RUN #4

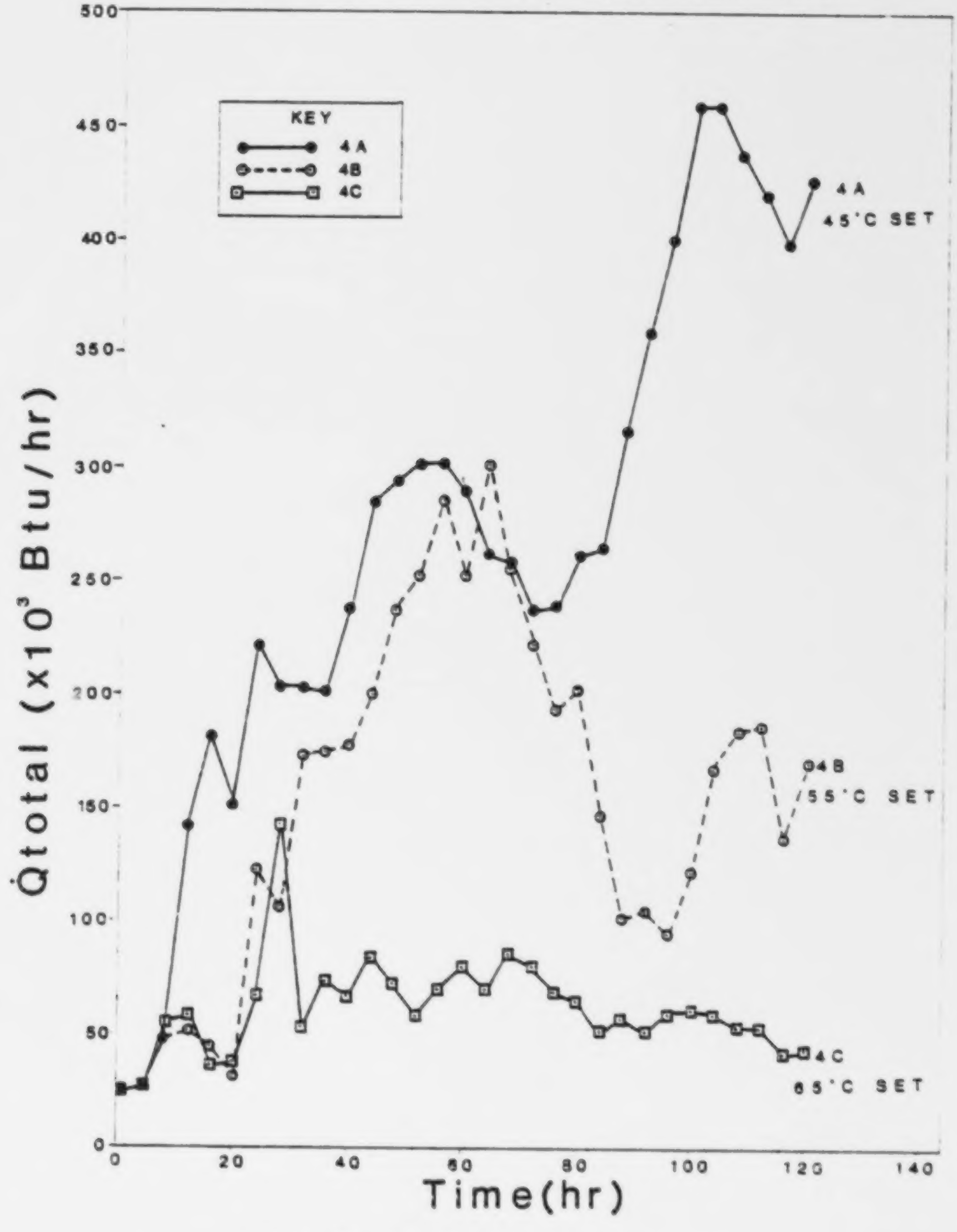


FIGURE 129